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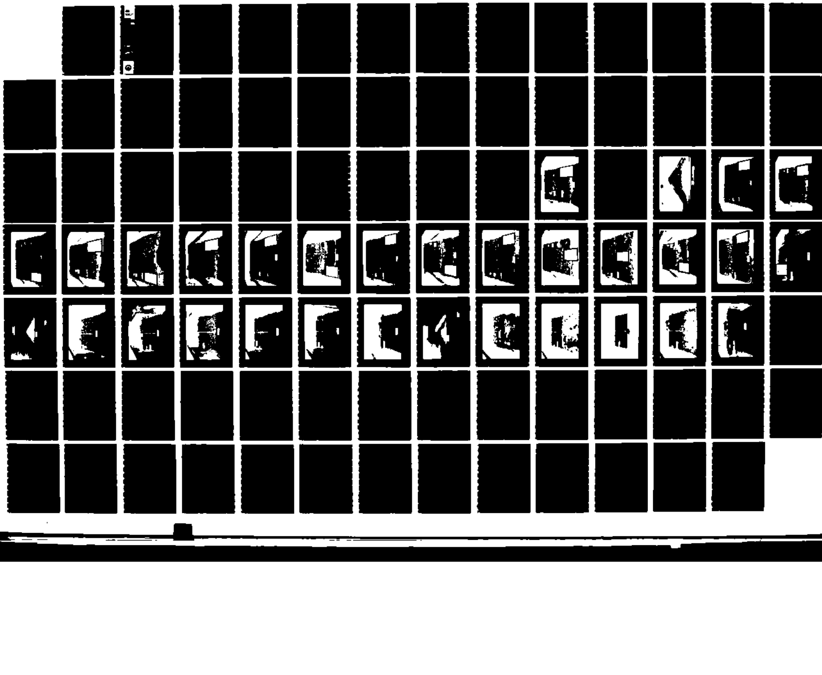

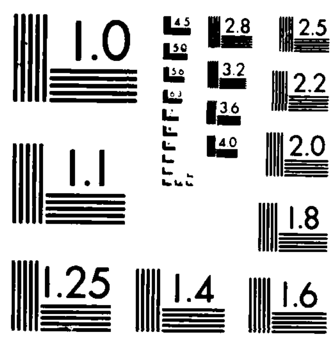

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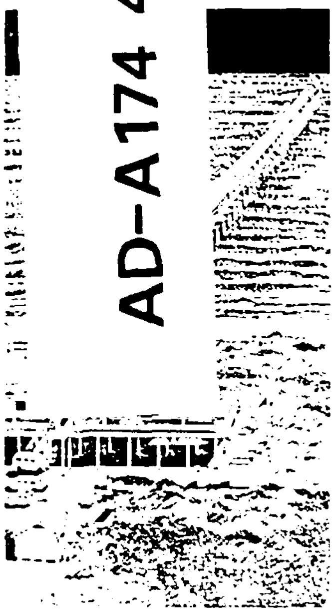

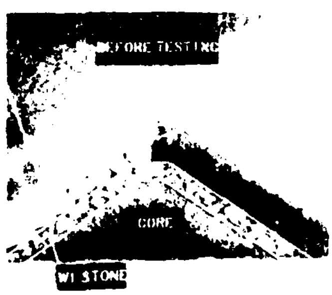

TECHNICAL REPORT CERC-86-10

STABILITY AND WAVE TRANSMISSION RESPONSE OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND BREAKWATER TRUNKS SUBJECTED TO EXTREME WAVE HEIGHTS

by

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Coastal Engineering Research Center

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The purpose of the investigation was to obtain design information for stone and dolos armor used on breakwater trunks and subjected to breaking and nonbreaking waves that exceeded the recommended design wave heights. Tests were planned in such a manner that sufficient data could be obtained to define a functional relationship between damage and relative wave height H/H_D where H is a selected extreme wave height and H_D is the design wave height. Also, transmitted wave heights were measured for all incident wave conditions.

Based on test results in which dolos and stone armor were used on breakwater trunks and subjected to nonbreaking waves in a d/L range of 0.10 to 0.25 and breaking waves in a d/L range of 0.04 to 0.14, the direction of wave approach was 90 deg, and the structures were initially designed for no overtopping, it was concluded that: (1)

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19. ABSTRACT (Continued).

a. Structures built to a 1V:1.5H slope generally tended to experience higher damage levels than those constructed on a 1V:2H slope.

b. Transmitted wave heights observed one-half and one wavelength behind the breakwaters were very similar.

PREFACE

Authority for the US Army Engineer Waterways Experiment Station (WES) to conduct this study was granted by the Office, Chief of Engineers (OCE), US Army Corps of Engineers, under Work Unit 31269, "Stability of Breakwaters," Coastal Structure Evaluation and Design Program, Coastal Engineering Area of Civil Works Research and Development. OCE Technical Monitors for this research were Messrs. John H. Lockhart, Jr., and John G. Housley.

The study was conducted by personnel of the Coastal Engineering Research Center (CERC), under general direction of Dr. James R. Houston, Chief, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC. Direct supervision was provided by Messrs. C. Eugene Chatham, Chief, Wave Dynamics Division, and D. Donald Davidson, Chief, Wave Research Branch. This report was prepared by Mr. Robert D. Carver, Project Engineer, and Mr. Willie G. Dubose, Engineering Technician. Tests were planned by Messrs. Carver and Dubose, and the model was operated by Mr. Dubose under the supervision of Mr. Carver. This report was edited by Ms. Shirley A. J. Hanshaw, Publications and Graphic Arts Division, WES.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	25.4	millimetres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

STABILITY AND WAVE TRANSMISSION RESPONSE OF STONE- AND DOLOS-ARMORED RUBBLE-MOUND BREAKWATER TRUNKS SUBJECTED TO EXTREME WAVE HEIGHTS

PART I: INTRODUCTION

Background

1. The experimental investigation described herein constitutes a portion of a research effort to provide engineering data for the safe and economical design of rubble-mound breakwaters. In this study, a rubble-mound breakwater is defined as a protective structure constructed with a core of quarry-run stone, sand, or slag and protected from wave action by one or more stone underlayers and a cover layer composed of selected quarrystone or specially shaped concrete armor units.

2. Rubble-mound breakwaters are used extensively throughout the world to provide protection from the destructive forces of storm waves for harbor and port facilities. A proposed structure may necessarily be designed for either nonbreaking or breaking waves depending upon positioning of the breakwater and severity of anticipated wave action during its economic life. Some local wave conditions may be of such magnitude that the protective cover layer must consist of specially shaped concrete armor units in order to provide stability; however, many local design requirements are most advantageously met by quarrystone armor. This particular report addresses the use of stone and dolos armor on breakwater trunks subjected to extreme wave heights.

3. Previous investigations have yielded a significant quantity of design information for quarrystone (Hudson 1958 and Carver 1980 and 1983), quadripods, tribars, modified cubes, hexapods, and modified tetrahedrons (Jackson 1968), dolosse (Carver and Davidson 1977 and Carver 1983), and toskane (Carver 1978). These studies have one common limitation, wave heights in exceedance of the design heights were not investigated. As more cost-effective, probabilistic design methods are used, it becomes increasingly important for the designer to be able to estimate damages (and their repair costs) that can be expected to occur if the breakwater is subjected to waves that exceed the selected design condition.

Purpose of Study

4. The purpose of the investigation reported herein was to obtain design information for stone and dolos armor used on breakwater trunks and subjected to breaking and nonbreaking waves that exceeded the recommended design wave heights. Tests were planned in such a manner that sufficient data could be obtained to define a functional relationship between damage and relative wave height (H/H_D) where H* is a selected extreme wave height, and H_D is the design wave height. Also, transmitted wave heights were measured for all incident wave conditions.

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

PART II: TESTS

Stability Scale Effects

5. If the absolute sizes of experimental breakwater materials and wave dimensions become too small, flow around the armor units enters the laminar regime; and the induced drag forces become a direct function of the Reynolds number. Under these circumstances prototype phenomena are not properly simulated, and stability scale effects are induced. Hudson (1975) presents a detailed discussion of the design requirements necessary to ensure the preclusion of stability scale effects in small-scale breakwater tests and concludes that scale effects will be negligible if the Reynolds stability number

$$R_N = \frac{g^{1/2} H^{1/2} \ell_a}{\nu}$$

where

g = acceleration due to gravity, ft/sec^2

H = wave height, ft

ℓ_a = characteristic length of armor unit, ft

is equal to or greater than 3×10^4. For all tests reported herein, the sizes of experimental armor and wave dimensions were selected such that scale effects were insignificant (i.e., R_N greater than 3×10^4).

Test Procedures

Method of constructing test sections

6. All experimental breakwater sections were constructed to reproduce as closely as possible results of the usual methods of constructing full-scale breakwaters. The core material was dampened as it was dumped by bucket or shovel into the flume and was compacted with hand trowels to simulate natural consolidation resulting from wave action during construction of the prototype structure. Once the core material was in place, it was sprayed with a low-velocity water hose to ensure adequate compaction of the material. Then the underlayer stone was added by shovel and smoothed to grade by hand or with trowels. No excessive pressure or compaction was applied during placement of the underlayer stone. Armor units used in the cover layers were placed in a

random manner corresponding to work performed by a general coastal contractor, i.e., they were individually placed but were laid down without special orientation or fitting. After each test series the armor units were removed from the breakwater, all of the underlayer stones were replaced to the grade of the original test section, and the armor was replaced.

Selection of critically breaking waves

7. For a given wave period and water depth, the most detrimental breaking wave (i.e., the most damaging wave) was determined by increasing the stroke adjustment on the wave generator in small increments and observing which wave produced the most severe breaking wave condition on the experimental structures. Wave heights of lower amplitude did not form the critical breaking wave, and wave heights of larger amplitude would break seaward of the test structures and dissipate their energy so that they were less damaging than the critically tuned wave.

8. A typical stability test series consisted of subjecting the test sections to attack by waves of given heights and periods until all damage had abated or the structures failed. Test sections were subjected to wave attack in approximately 30-sec intervals, between which the wave generator was stopped and the waves were allowed to decay to zero height. This procedure was necessary to prevent the structures from being subjected to an undefined wave system created by reflections from the experimental breakwater and wave generator. Newly built test sections were subjected to a short duration (five or six 30-sec intervals) of shakedown using a wave equal in height to about one-half the design wave. This procedure provided a means of allowing consolidation and armor unit seating that would normally occur during prototype construction.

Method of determining damage

9. In order to evaluate and compare breakwater stability test results, it is necessary to quantify the changes that have taken place in a given structure during attack by waves of specified characteristics. The US Army Engineer Waterways Experiment Station (WES) developed a method of measuring the percent damage incurred by a test section during the early 1950's. This method has proven satisfactory and was used as a means for analyzing and comparing the stability tests delineated herein.

10. The WES damage-measurement technique requires that the cross-sectional area occupied by armor units be determined for each stability test

section. Armor unit area is computed from elevations (soundings) taken at closely spaced grid-point locations before the armor is placed on the underlayer, after the armor has been placed but before the section has been subjected to wave attack, and, finally, after wave attack. Elevations are obtained with a sounding rod equipped with a circular spirit level for plumbing, a scale graduated in thousandths of a foot, and a ball-and-socket foot for adjustment to the irregular surface of the breakwater slope. The diameter (Diam) in inches of the circular foot of the sounding rod was related to the size of the material being sounded by the following equation:

$$\text{Diam} = C \left(\frac{W_a}{\gamma_a}\right)^{1/3}$$

where

W_a = weight, lb

γ_a = specific weight, pcf

C = 6.8 and 13.7 for stone and dolosse, respectively. A series of sounding tests in which both the weight of the armor and the diameter of the sounding foot were varied indicated that the above relation would give a measured thickness which visually appeared to represent an acceptable two-layer thickness.

11. Sounding data for each test section were obtained as follows: after the underlayer was in place, soundings were taken on the slopes of the structure along rows beginning at and parallel to the longitudinal center line of the structure and extending in 0.25-ft* horizontal increments until the edge of the armor was reached. On each parallel row, sounding points, spaced at 0.25-ft increments, were measured. The 0.5 ft of structure next to each wall was not considered because of the possibility of discontinuity effects between armor units and the flume walls. Soundings were taken at the same points once the armor was in place and again after the structure had been subjected to wave attack.

12. Sounding data from each stability test were reduced in the following manner. The individual sounding points obtained on each parallel row were averaged to yield an average elevation at the bottom of the armor layer before the armor was placed and then at the top of the armor layer before and after

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* A table of factors for converting non-SI to SI (metric) units is presented on page 3.

testing. From these values, the cross-sectional armor area before testing and the area from which armor units were displaced (either downslope or off the section) were calculated. Damage was then determined from the following relation:

$$\text{Percent damage} = \frac{A_2}{A_1} (100)$$

where

A_2 = area before testing, ft^2

A_1 = area from which armor units have been displaced, ft^2

The percentage given by the WES sounding technique is, therefore, a measurement of an end area which converts to an average volume of armor material that has been moved from its original location (either downslope or off-structure).

Test Equipment and Materials

Equipment used

13. Companion concrete wave flumes, 5.0 and 6.75 ft wide, 4.0 ft deep, and 119.0 ft long, were used for all nonbreaking wave tests. These flat-bottomed flumes are equipped with a common vertical displacement wave generator capable of producing sinusoidal waves of various periods and heights. Test sections in each of the parallel flumes were 85 ft from the wave generator. All breaking wave tests were conducted in a 5-ft-wide, 4-ft-deep, 119-ft-long concrete wave flume with test sections installed about 90 ft from a vertical displacement wave generator. A thin divider was installed in the center of the test section area, thus yielding two 2.5-ft-wide sections. The first 10 ft of flume bottom, immediately seaward of the test sections, was molded on a 1V on 10H slope, while the remaining 80 ft was flat. The generator is capable of producing sinusoidal waves of various periods and heights. For all tests, waves of the required characteristics were generated by varying the frequency and amplitude of the plunger motion. Changes in water surface elevation as a function of time (wave heights) were measured by electrical wave height gages in the vicinity of where the toe of the test sections was to be placed and recorded on chart paper by an electrically operated oscillograph. The electrical output of the wave gages was directly proportional to their submergence depth.

Materials used

14. Rough hand-shaped granitic stone W_a with an average length of approximately two times its width, average weight of 0.55 lb ($\pm$0.025 lb), and a specific weight of 167 pcf was used to armor the stone sections. Dolos sections were armored with 0.276-lb units that have a specific weight of 142.2 pcf. Sieve-sized limestone (γ_a = 165.0 pcf) was used for the underlayers and core.

Selection of Test Conditions

Nonbreaking wave tests

15. Nonbreaking wave tests were conducted on dolos armor only in a water depth of 2.0 ft. Comparative data for nonbreaking wave conditions already exist for stone and other types of selected armor units in the Shore Protection Manual (SPM) (1984). Sea-side slopes of 1V on 1.5H and 1V on 2H were investigated, while the beach-side slope was held constant at 1V on 1.5H. Relative depths d/L ranged from 0.10 to 0.25, and relative wave heights H/H_D ranged from 1.0 to 1.4. Design wave heights were calculated from the Hudson Stability Equation (SPM 1984) using a stability coefficient of 31 (Carver and Davidson 1977). For the 0.276-lb units placed on a 1V on 1.5H slope, the predicted design wave height is 0.57 ft. A similar calculation yielded a design wave height of 0.63 ft for the 1V on 2H sea-side slope. The types of sections tested are shown in Plate 1 and Photos 1, 2, 3, 10, and 11.

Breaking wave tests

16. Breaking wave tests were conducted using both stone and dolos armor. A review of past site-specific stability projects and hydrographic data showed that typical prototype sea-bottom slopes could range from almost flat to as steep as 1V on 10H. Realizing that wave deformation and severity of breaking action increase as bottom slope increases and since time restraints would allow testing of only one foreslope, it was decided to use a 1V on 10H slope, thus ensuring severe depth-limited breaking wave action (plunging breakers). When breaking directly on the structure, this type of breaking wave normally causes the most damage to rubble-mound structures.

17. By nondimensionalizing design conditions from site-specific projects, it was found that a d/L range of 0.04 to 0.14 should include most prototype conditions encountered in breaking wave stability designs. A review

of capabilities of the available flume and wave generator showed that this range of d/L values could be achieved for a reasonable range of testing depths.

18. The wave flume was calibrated for depths from 0.40 to 0.95 ft in 0.05-ft increments at d/L values of 0.04, 0.06, 0.08, 0.10, 0.12, and 0.14. This range of depths and, consequently, breaking wave heights proved to be compatible with the selected armor weights and sea-side breakwater slopes.

19. All breaking wave stability and wave transmission tests were conducted on sections of the type shown in Plate 2 and Photos 18, 19, 22, 25, 26, and 29. Sea-side slopes of 1V on 1.5H and 1V on 2H were investigated, while the beach-side slope was held constant at 1V on 1.5H. Structure heights varied from 1.0 to 1.2 ft. The height necessary to prevent wave overtopping for the base design conditions was determined by the combination of slope, armor type, and water depth being investigated. Initial design wave conditions were selected from Carver (1983) according to a no-damage design criterion (i.e., less than 5 percent damage).

PART III: TEST RESULTS

Stability Tests

Nonbreaking waves

20. Nonbreaking wave stability test results for dolos armor are summarized in Table 1. Presented therein are experimentally determined damages as functions of relative depth, relative wave height, and breakwater slope. The number of armor units per given surface area A is $N = 0.83V^{-2/3}$ where V = volume of an individual armor unit, and 0.83 is a coefficient corresponding to $n = 2$, $k_{\Delta} = 0.94$, and $P = 56$ percent. Photos 4-9 and 12-17 show the after testing conditions of the structures.

21. For each test series, damage values from the indicated areas of the test sections (i.e., sea side, beach side, or total) that showed the largest damages were extracted from Table 1 and plotted in Plates 3 through 8. Data from the test section with the 1V on 1.5H sea-side slope show that, in general, damage increases slowly as H/H_D increases from 1.0 to 1.2; however, when $H/H_D = 1.3$ is reached, damage increases rapidly. The 1V on 2H sea-side slope test section indicated similiar but less drastic results. Upper limit curves for each data set are presented also in Plates 3 through 8.

Breaking waves

22. Breaking wave stability test results for dolos and stone armor are presented in Tables 2 and 3, respectively. Presented therein are experimentally determined damages as functions of relative depth, relative wave height, and breakwater slope. Damage is presented as a function of relative wave height in Plates 9 through 20. As with the nonbreaking wave data, upper limit curves are fit to each data set. Photos 20, 21, 23, 24, 27, 28, 30, and 31 show the final stability condition of the test sections. In general, data trends for the breaking wave conditions on dolosse are similiar to those for nonbreaking wave conditions, except the initial rate of damage is greater and damage increases at a more constant pace. Breaking wave conditions cause stone damage to increase but at a lesser overall rate than for dolosse.

23. Weights of the dolosse and stone were 0.276 and 0.55 lb, respectively. The following ranges of water depths, wave periods and heights, relative depths, and relative wave heights were investigated.

Variables	Stone	Dolosse
Water depth, ft	0.40-0.95	0.45-0.95
Wave period, sec	1.18-2.82	1.29-2.02
Wave height, ft	0.37-0.66	0.45-0.77
Relative depth	0.04-0.12	0.06-0.14
Relative wave height	1.00-1.62	1.00-1.54

The number of armor units per given surface area A was $N = 1.26\ V^{-2/3}$, with $n = 2$, $k_\Delta = 1.00$, and $P = 37$ percent for stone armor, and $N = 0.83\ V^{-2/3}$ with $n = 2$, $k_\Delta = 0.94$, and $P = 56$ percent for dolos armor. The variable V is defined as the volume of an individual armor unit.

Summary of results

24. Table 4 summarizes damage test results as functions of relative wave height, armor type, breakwater slope, and wave form. Damage values presented in Table 4 were extracted from the upper limit curves given in Plates 3 through 21. Information presented in Table 4 may be useful in estimating anticipated annual repair costs, given appropriate long-term wave statistics for the site. These data are applicable to structures that are initially designed for no overtopping where the combinations of water depth and wave period yield relative depth d/L values that are within the range tested (0.10 to 0.25 for nonbreaking waves and 0.04 to 0.14 for breaking waves). It should be noted that effects on stability of dolos breakage were not simulated; thus, expected prototype damages for the higher relative wave heights may be significantly greater than those presented herein.

Discussion

25. Due to the inherent variability of stability test results for wave conditions in excess of the design wave height, it is felt that use of the upper limit damage values is reasonable. It is interesting to note that the structures built to a 1V on 1.5H slope generally tend to experience higher levels of damage than those constructed on a 1V on 2H slope.

Wave Transmission Tests

26. Transmitted wave heights were measured for all wave conditions investigated in the stability tests. Wave gages were positioned about one-half and one wavelength behind the breakwater centerline. Results of these tests are presented in Tables 5 through 10. Considering the small

random variations inherent in test waves within a given wave train, results appear to be consistent. Also, as one would expect, wave heights are very similar at both gage locations.

27. Tables 11 through 13 and Plates 21 through 26 present relative transmitted wave height H_t/H_{t_D} as a function of relative wave height. (Relative transmitted wave height is the ratio of the transmitted height for incident wave conditions larger than the design wave height relative to the transmitted wave height for the design wave condition.) Upper limit curves are presented also in Plates 21 through 26.

28. Table 14 summarizes expected relative transmitted wave heights as functions of relative wave height, armor type, breakwater slope, and wave form. Values presented in Table 14 were obtained from the upper limit curves given in Plates 21 through 26. When the values observed at $L/2$ and L were slightly different, the larger was selected for inclusion in Table 14. Information presented in Table 14 may be used to estimate anticipated transmitted wave heights for incident wave conditions in excess of the design wave height if the structure is initially designed for no overtopping and the relative depths d/L are within the range tested (0.10 to 0.25 for nonbreaking waves and 0.04 to 0.14 for breaking waves).

PART IV: CONCLUSIONS

29. Based on tests and results described herein, in which dolos and stone armor are used on breakwater trunks and subjected to nonbreaking waves in a d/L range of 0.10 to 0.25 and breaking waves in a d/L range of 0.04 to 0.14, the direction of wave approach is 90 deg, and the structures are initially designed for no overtopping, it is concluded that

- a. Data presented in Table 4 are reasonable percentages of damage for wave heights higher than the design event.
- b. Expected prototype damages for the higher relative wave heights may be significantly greater than those presented herein for dolos armor since breakage of the armor units was not simulated.
- c. Structures built to a 1V on 1.5H slope generally tended to experience higher damage levels than those constructed on a 1V on 2H slope.
- d. Information presented in Table 14 may be used to estimate anticipated transmitted wave heights for incident wave conditions in excess of the design wave height.
- e. Transmitted wave heights observed one-half and one wavelength behind the breakwaters were very similar.

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Table 1

Damage Summary for Dolosse Subjected to Nonbreaking Waves; $W_a = 0.276$ lb; $\gamma_a = 142.2$ pcf;

$d = 2.00$ ft; Cot $\alpha = 1.5$ and 2.0

				Damage for Indicated Structure and Armor Area, percent					
				Structure 1			Structure 2		
T, sec	H, ft	d/L	H/H_D	Sea Side	Beach Side	Total	Sea Side	Beach Side	Total
				Test Series 1; Cot α = 1.5					
1.31	0.57	0.25	1.00	2.2	1.0	1.7	0.2	1.9	0.8
1.31	0.63	0.25	1.10	2.3	1.7	2.2	0.7	1.5	1.0
1.31	0.68	0.25	1.20	6.4	1.8	4.7	1.6	1.6	1.6
1.31	0.74	0.25	1.30	60.3	30.1	49.3	3.5	2.2	2.9
				Test Series 2; Cot α = 1.5					
1.89	0.57	0.15	1.00	1.7	0.7	1.3	1.2	0.2	0.9
1.89	0.63	0.15	1.10	1.5	1.8	1.6	2.1	1.5	1.9
1.89	0.68	0.15	1.20	5.2	0.8	3.6	4.0	1.3	3.1
1.89	0.74	0.15	1.30	12.4	1.8	8.4	68.8	43.5	59.8
				Test Series 3; Cot α = 1.5					
2.65	0.57	0.10	1.00	3.2	0.3	2.2	4.6	0.7	3.2
2.65	0.63	0.10	1.10	4.0	0.2	2.7	4.4	1.0	3.2
2.65	0.68	0.10	1.20	4.3	0.9	3.1	4.4	0.9	3.2
2.65	0.74	0.10	1.30	4.2	3.2	3.9	5.1	1.7	3.8
2.65	0.80	0.10	1.40	6.5	4.8	6.0	5.6	4.1	5.1
				Test Series 4; Cot α = 2.0					
1.31	0.63	0.25	1.00	2.1	2.4	2.2	1.2	0.3	0.9
1.31	0.69	0.25	1.10	3.3	3.0	3.2	1.4	0.2	1.0
1.31	0.76	0.25	1.20	4.1	4.0	4.1	1.6	0.5	1.2
				Test Series 5; Cot α = 2.0					
1.89	0.63	0.15	1.00	3.0	0.9	2.4	4.2	0.2	3.0
1.89	0.69	0.15	1.10	3.7	1.6	3.1	3.7	1.9	2.7

(Continued)

Table 1 (Concluded)

T, sec	H, ft	d/L	H/H_D	Damage for Indicated Structure and Armor Area, percent — Structure 1: Sea Side	Structure 1: Beach Side	Structure 1: Total	Structure 2: Sea Side	Structure 2: Beach Side	Structure 2: Total
				Test Series 5; Cot α = 2.0 (Continued)					
1.89	0.76	0.15	1.20	5.1	1.4	4.0	4.9	1.2	3.8
1.89	0.82	0.15	1.30	7.8	1.8	6.0	5.2	0.1	3.6
1.89	0.88	0.15	1.40	18.9	3.2	14.2	7.1	1.6	5.4
				Test Series 6; Cot α = 2.0					
2.65	0.63	0.10	1.00	0.8	0.3	0.6	2.1	0.5	1.7
2.65	0.69	0.10	1.10	0.6	0.4	0.5	0.6	0.3	0.5
2.65	0.76	0.10	1.20	1.5	0.6	1.3	2.3	1.2	2.0
2.65	0.82	0.10	1.30	1.6	2.2	1.8	5.0	2.1	4.1

Table 2

Damage Summary for Dolosse Subjected to Breaking Waves; $W_a = 0.276$ lb; $\gamma_a = 142.2$ pcf;

Cot α = 1.5 and 2.0

					Damage for Indicated Structure and Armor Area, percent					
					Structure 1			Structure 2		
T, sec	H, ft	d, ft	d/L	H/H_D	Sea Side	Beach Side	Total	Sea Side	Beach Side	Total
				Test Series 1; Cot α = 1.5						
1.62	0.45	0.50	0.08	1.00	5.3	0.0	2.7	2.7	0.7	1.7
1.45	0.52	0.60	0.10	1.16	3.7	0.0	1.9	4.0	0.5	2.1
1.85	0.60	0.65	0.08	1.33	9.3	0.5	4.9	8.1	0.8	4.1
1.67	0.66	0.80	0.10	1.47	32.7	2.3	17.4	13.4	0.5	6.5
				Test Series 2; Cot α = 1.5						
2.02	0.46	0.45	0.06	1.00	1.9	1.6	1.8	1.8	1.5	1.6
1.29	0.51	0.65	0.12	1.11	3.2	1.4	2.3	7.2	0.2	3.8
1.34	0.55	0.70	0.12	1.20	4.9	2.3	3.6	7.5	1.2	4.4
1.37	0.61	0.95	0.14	1.33	7.8	1.8	4.8	8.4	1.8	5.2
1.52	0.64	0.90	0.12	1.39	11.1	2.2	6.6	9.6	3.6	6.7
1.56	0.66	0.95	0.12	1.43	13.6	2.1	7.9	14.4	2.5	8.6
1.73	0.71	0.85	0.10	1.54	27.0	2.4	14.7	17.0	2.9	10.1
				Test Series 3; Cot α = 2.0						
1.30	0.56	0.85	0.14	1.00	3.6	1.4	2.6	4.0	2.1	3.2
1.47	0.63	0.85	0.12	1.13	8.2	1.4	5.1	7.5	1.1	4.5
1.56	0.66	0.95	0.12	1.18	13.0	0.7	7.4	10.3	1.1	6.0
1.73	0.71	0.85	0.10	1.27	20.2	1.2	11.4	11.3	1.2	6.6
1.78	0.77	0.90	0.10	1.38	29.5	1.4	16.6	10.7	1.1	6.3
				Test Series 4; Cot α = 2.0						
1.70	0.54	0.55	0.08	1.00	0.6	0.8	0.7	3.2	0.3	1.9
1.85	0.60	0.65	0.08	1.11	4.0	0.7	2.5	7.9	0.6	4.6
1.99	0.70	0.75	0.08	1.30	7.5	0.7	4.4	11.0	1.7	6.7
1.78	0.77	0.90	0.10	1.43	16.1	1.0	9.2	23.2	1.1	13.1

Table 3

Damage Summary for Stone Subjected to Breaking Waves; W_a = 0.55 lb; γ_a = 167.0 pcf;

Cot α = 1.5 and 2.0

					Damage for Indicated Structure and Armor Area, percent					
					Structure 1			Structure 2		
T, sec	H, ft	d, ft	d/L	H/H_D	Sea Side	Beach Side	Total	Sea Side	Beach Side	Total
					Test Series 1; Cot α = 1.5					
1.18	0.38	0.55	0.12	1.00	3.5	2.0	2.7	4.9	0.4	2.6
1.24	0.45	0.60	0.12	1.18	16.9	2.1	9.3	15.0	1.1	8.1
1.29	0.51	0.65	0.12	1.34	22.4	2.2	11.9	25.5	2.1	13.8
1.34	0.55	0.70	0.12	1.45	26.1	3.4	14.3	31.4	2.8	17.1
1.62	0.58	0.75	0.10	1.53	45.7	28.9	37.1	52.3	32.5	42.3
					Test Series 2; Cot α = 1.5					
1.45	0.37	0.40	0.08	1.00	1.2	0.0	0.6	3.5	0.0	1.7
1.90	0.42	0.40	0.06	1.14	8.4	0.1	4.1	5.7	0.1	3.0
2.02	0.46	0.45	0.06	1.24	8.7	0.0	4.3	17.0	0.3	8.6
1.70	0.54	0.55	0.08	1.46	14.7	0.4	7.5	18.3	0.7	9.5
2.32	0.58	0.60	0.06	1.57	20.6	0.5	10.5	20.9	0.9	10.8
1.85	0.60	0.65	0.08	1.62	27.5	2.1	14.8	24.5	1.7	13.0
					Test Series 3; Cot α = 2.0					
1.24	0.45	0.60	0.12	1.00	2.3	0.4	1.4	2.8	1.0	1.9
1.29	0.51	0.65	0.12	1.13	5.2	0.6	3.1	8.1	0.7	4.7
1.34	0.55	0.70	0.12	1.22	11.8	2.0	7.4	13.4	1.6	8.0
1.47	0.63	0.85	0.12	1.40	22.9	2.6	13.8	23.5	5.4	15.4
1.56	0.66	0.95	0.12	1.47	24.8	14.0	20.0	23.7	15.8	20.3
					Test Series 4; Cot α = 2.0					
2.82	0.42	0.40	0.04	1.00	1.6	0.5	1.1	2.8	0.7	1.9
2.02	0.46	0.45	0.06	1.10	1.1	0.8	1.0	3.3	0.7	2.0
1.70	0.54	0.55	0.08	1.29	4.1	0.5	2.5	4.7	0.4	2.8
2.32	0.58	0.60	0.06	1.38	7.1	0.6	4.1	8.2	0.3	4.6
1.85	0.60	0.65	0.08	1.43	11.9	0.9	6.8	15.1	1.3	8.9
1.67	0.66	0.80	0.10	1.57	27.9	1.3	15.7	22.2	0.9	12.5

Table 4

Damage Summary for Dolos and Stone Armor

Armor Type	Wave Form	Cot α	H/H_D	Damage for Indicated Armor Area, percent: Sea Side	Beach Side	Total
Dolos	Nonbreaking	1.5	1.00	3	1	2
		1.5	1.10	4	2	3
		1.5	1.20	7	3	5
		1.5	1.30	69	44	60
		2.0	1.00	2	2	2
		2.0	1.10	3	3	3
		2.0	1.20	4	4	4
		2.0	1.30	8	4	6
		2.0	1.40	19	5	14
Dolos	Breaking	1.5	1.00	5	2	3
		1.5	1.10	7	2	4
		1.5	1.20	7	3	5
		1.5	1.30	9	3	5
		1.5	1.40	12	3	7
		2.0	1.00	4	2	3
		2.0	1.10	7	2	5
		2.0	1.20	15	2	8
		2.0	1.30	23	2	13
		2.0	1.40	32	2	18
Stone	Breaking	1.5	1.00	5	2	3
		1.5	1.10	7	2	6
		1.5	1.20	18	3	10
		1.5	1.30	24	3	12
		1.5	1.40	29	3	15
		1.5	1.50	41	22	32
		2.0	1.00	3	1	2
		2.0	1.10	7	2	4
		2.0	1.20	12	2	7
		2.0	1.30	18	3	11
		2.0	1.40	23	6	16
		2.0	1.50	27	20	23

Table 5

Transmitted Wave Heights Measured One-Half Wavelength Behind Breakwater for Dolosse Subjected to Nonbreaking Waves; W_a = 0.276 lb; γ_a = 142.2 pcf; d = 2.00 ft; Cot α = 1.5 and 2.0

T, sec	H, ft	H/H_D	Transmitted Wave Height, ft Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
			Test Series 1; Cot α = 1.5						
1.31	0.57	1.00	0.007	0.009	0.008	0.009	0.008	0.008	0.001
1.31	0.63	1.10	0.008	0.009	0.009	0.009	0.009	0.009	0.001
1.31	0.68	1.20	0.012	0.008	0.013	0.013	0.014	0.012	0.002
1.31	0.74	1.30	0.012	0.013	0.012	0.015	0.014	0.013	0.001
			Test Series 2; Cot α = 1.5						
1.89	0.57	1.00	0.017	0.017	0.016	0.016	0.017	0.017	0.001
1.89	0.63	1.10	0.018	0.017	0.018	0.018	0.018	0.018	0.001
1.89	0.68	1.20	0.024	0.023	0.022	0.023	0.023	0.023	0.001
1.89	0.74	1.30	0.042	0.042	0.044	0.046	0.044	0.044	0.002
			Test Series 3; Cot α = 1.5						
2.65	0.57	1.00	0.019	0.020	0.018	0.019	0.020	0.019	0.001
2.65	0.63	1.10	0.020	0.021	0.020	0.020	0.019	0.020	0.001
2.65	0.68	1.20	0.027	0.026	0.027	0.028	0.028	0.027	0.001
2.65	0.74	1.30	0.040	0.040	0.038	0.041	0.040	0.040	0.001
2.65	0.80	1.40	0.052	0.055	0.054	0.053	0.055	0.054	0.001
			Test Series 4; Cot α = 2.0						
1.31	0.63	1.00	0.005	0.006	0.006	0.007	0.005	0.006	0.001
1.31	0.69	1.10	0.007	0.008	0.007	0.006	0.007	0.007	0.001
1.31	0.76	1.20	0.010	0.008	0.009	0.009	0.010	0.009	0.001

(Continued)

Table 5 (Concluded)

T, sec	H, ft	H/H_D	Transmitted Wave Height, ft Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
				Test Series 5; Cot α = 2.0					
1.89	0.63	1.00	0.013	0.012	0.011	0.012	0.012	0.012	0.001
1.89	0.69	1.10	0.014	0.013	0.014	0.013	0.015	0.014	0.001
1.89	0.76	1.20	0.021	0.021	0.022	0.022	0.022	0.022	0.001
1.89	0.82	1.30	0.027	0.029	0.030	0.034	0.033	0.031	0.003
1.89	0.88	1.40	0.045	0.041	0.043	0.037	0.045	0.042	0.003
				Test Series 6; Cot α = 2.0					
2.65	0.63	1.00	0.014	0.014	0.015	0.014	0.015	0.014	0.001
2.65	0.69	1.10	0.014	0.016	0.015	0.014	0.014	0.015	0.001
2.65	0.76	1.20	0.017	0.018	0.017	0.018	0.017	0.017	0.001
2.65	0.82	1.30	0.022	0.023	0.023	0.022	0.023	0.023	0.001

Table 6

Transmitted Wave Heights Measured One Wavelength Behind Breakwater for Dolosse Subjected to Nonbreaking Waves; W_a = 0.276 lb; γ_a = 142.2 pcf; d = 2.0 ft; Cot α = 1.5 and 2.0

T, sec	H, ft	H/H_D	Transmitted Wave Height, ft						
			Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
			Test Series 1; Cot α = 1.5						
1.31	0.57	1.00	0.007	0.007	0.008	0.009	0.007	0.008	0.001
1.31	0.63	1.10	0.009	0.009	0.008	0.008	0.008	0.008	0.001
1.31	0.68	1.20	0.012	0.011	0.013	0.012	0.014	0.012	0.001
1.31	0.74	1.30	0.011	0.013	0.011	0.013	0.012	0.012	0.001
			Test Series 2; Cot α = 1.5						
1.89	0.57	1.00	0.017	0.017	0.017	0.017	0.017	0.017	0.000
1.89	0.63	1.10	0.018	0.018	0.019	0.018	0.018	0.018	0.001
1.89	0.68	1.20	0.022	0.021	0.022	0.022	0.021	0.022	0.001
1.89	0.74	1.30	0.039	0.036	0.039	0.038	0.037	0.038	0.001
			Test Series 3; Cot α = 1.5						
2.65	0.57	1.00	0.021	0.020	0.020	0.020	0.021	0.020	0.001
2.65	0.63	1.10	0.021	0.022	0.020	0.022	0.022	0.021	0.001
2.65	0.68	1.20	0.026	0.027	0.026	0.028	0.027	0.027	0.001
2.65	0.74	1.30	0.039	0.036	0.038	0.039	0.037	0.038	0.001
2.65	0.80	1.40	0.050	0.053	0.050	0.048	0.054	0.051	0.002
			Test Series 4; Cot α = 2.0						
1.31	0.63	1.00	0.006	0.005	0.006	0.004	0.005	0.005	0.001
1.31	0.69	1.10	0.006	0.006	0.007	0.005	0.006	0.006	0.001
1.31	0.76	1.20	0.008	0.007	0.008	0.009	0.007	0.008	0.001

Continued

Table 6 (Concluded)

T, sec	H, ft	H/H_D	Transmitted Wave Height, ft						
			Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
			Test Series 5; Cot α = 2.0						
1.89	0.63	1.00	0.012	0.011	0.010	0.011	0.010	0.011	0.001
1.89	0.69	1.10	0.014	0.013	0.014	0.013	0.013	0.013	0.001
1.89	0.76	1.20	0.017	0.015	0.017	0.016	0.018	0.017	0.001
1.89	0.82	1.30	0.023	0.024	0.027	0.031	0.026	0.026	0.003
1.89	0.88	1.40	0.041	0.036	0.032	0.035	0.035	0.036	0.003
			Test Series 6; Cot α = 2.0						
2.65	0.63	1.00	0.014	0.013	0.013	0.014	0.014	0.014	0.001
2.65	0.69	1.10	0.014	0.015	0.014	0.013	0.014	0.014	0.001
2.65	0.76	1.20	0.017	0.016	0.017	0.018	0.017	0.017	0.001
2.65	0.82	1.30	0.025	0.024	0.020	0.024	0.023	0.023	0.002

Table 7

Transmitted Wave Heights Measured One-Half Wavelength Behind Breakwater for Dolosse Subjected to Breaking Waves; $W_a = 0.276$ lb; $\gamma_a = 142.2$ pcf; Cot α = 1.5 and 2.0

					Transmitted Wave Height, ft						
T , sec	H , ft	d , ft	d/L	H/H_D	Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
					Test Series 1; Cot α = 1.5						
1.62	0.45	0.50	0.08	1.00	0.006	0.007	0.006	0.007	0.007	0.007	0.001
1.45	0.52	0.60	0.10	1.16	0.007	0.007	0.007	0.007	0.007	0.007	0.000
1.85	0.60	0.65	0.08	1.33	0.015	0.014	0.013	0.013	0.015	0.014	0.001
1.67	0.66	0.80	0.10	1.47	0.028	0.028	0.027	0.028	0.028	0.028	0.001
					Test Series 2; Cot α = 1.5						
2.02	0.46	0.45	0.06	1.00	0.006	0.006	0.006	0.006	0.006	0.006	0.000
1.29	0.51	0.65	0.12	1.11	0.007	0.007	0.007	0.007	0.007	0.007	0.000
1.34	0.55	0.70	0.12	1.20	0.009	0.009	0.009	0.009	0.009	0.009	0.000
1.37	0.61	0.95	0.14	1.33	0.019	0.016	0.018	0.018	0.018	0.018	0.001
1.52	0.64	0.90	0.12	1.39	0.025	0.023	0.023	0.023	0.024	0.024	0.001
1.56	0.66	0.95	0.12	1.43	0.033	0.026	0.030	0.027	0.029	0.029	0.003
1.73	0.71	0.85	0.10	1.54	0.031	0.029	0.032	0.030	0.031	0.031	0.001
					Test Series 3; Cot α = 2.0						
1.30	0.56	0.85	0.14	1.00	0.007	0.007	0.007	0.007	0.007	0.007	0.000
1.47	0.63	0.85	0.12	1.13	0.009	0.008	0.008	0.008	0.008	0.008	0.001
1.56	0.66	0.95	0.12	1.18	0.012	0.013	0.013	0.012	0.013	0.013	0.001
1.73	0.71	0.85	0.10	1.27	0.012	0.011	0.011	0.011	0.011	0.011	0.001
1.78	0.77	0.90	0.10	1.38	0.017	0.017	0.017	0.017	0.017	0.017	0.000
					Test Series 4; Cot α = 2.0						
1.70	0.54	0.55	0.08	1.00	0.005	0.005	0.004	0.005	0.005	0.005	0.001
1.85	0.60	0.65	0.08	1.11	0.007	0.006	0.006	0.006	0.006	0.006	0.001
1.99	0.70	0.75	0.08	1.30	0.009	0.009	0.008	0.009	0.009	0.009	0.001
1.78	0.77	0.90	0.10	1.43	0.013	0.012	0.012	0.013	0.013	0.013	0.001

Table 8

Transmitted Wave Heights Measured One Wavelength Behind Breakwater for Dolosse Subjected to Breaking Waves; W_a = 0.276 lb; γ_a = 142.2 pcf; Cot α = 1.5 and 2.0

T, sec	H, ft	d, ft	d/L	H/H_D	Transmitted Wave Height, ft: Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
					Test Series 1; Cot α = 1.5						
1.62	0.45	0.50	0.08	1.00	0.007	0.008	0.007	0.007	0.008	0.007	0.001
1.45	0.52	0.60	0.10	1.16	0.007	0.007	0.008	0.007	0.007	0.007	0.001
1.85	0.60	0.65	0.08	1.33	0.015	0.014	0.015	0.013	0.015	0.014	0.001
1.67	0.66	0.80	0.10	1.47	0.027	0.028	0.028	0.029	0.029	0.028	0.001
					Test Series 2; Cot α = 1.5						
2.02	0.46	0.45	0.06	1.00	0.006	0.006	0.006	0.006	0.006	0.006	0.000
1.29	0.51	0.65	0.12	1.11	0.008	0.008	0.008	0.008	0.008	0.008	0.000
1.34	0.55	0.70	0.12	1.20	0.010	0.009	0.009	0.009	0.009	0.009	0.001
1.37	0.61	0.95	0.14	1.33	0.018	0.016	0.017	0.018	0.017	0.017	0.001
1.52	0.64	0.90	0.12	1.39	0.024	0.022	0.022	0.022	0.023	0.023	0.001
1.56	0.66	0.95	0.12	1.43	0.031	0.027	0.028	0.027	0.028	0.028	0.002
1.73	0.71	0.85	0.10	1.54	0.029	0.030	0.029	0.031	0.030	0.030	0.001
					Test Series 3; Cot α = 2.0						
1.30	0.56	0.85	0.14	1.00	0.007	0.007	0.007	0.007	0.007	0.007	0.000
1.47	0.63	0.85	0.12	1.13	0.009	0.008	0.009	0.009	0.009	0.009	0.001
1.56	0.66	0.95	0.12	1.18	0.014	0.013	0.013	0.013	0.013	0.013	0.001
1.73	0.71	0.85	0.10	1.27	0.012	0.010	0.011	0.011	0.011	0.011	0.001
1.78	0.77	0.90	0.10	1.38	0.017	0.017	0.017	0.017	0.017	0.017	0.000
					Test Series 4; Cot α = 2.0						
1.70	0.54	0.55	0.08	1.00	0.004	0.004	0.004	0.005	0.004	0.004	0.001
1.85	0.60	0.65	0.08	1.11	0.007	0.007	0.007	0.007	0.007	0.007	0.000
1.99	0.70	0.75	0.08	1.30	0.010	0.010	0.010	0.010	0.009	0.010	0.001
1.78	0.77	0.90	0.10	1.43	0.013	0.014	0.013	0.013	0.013	0.013	0.001

Table 9

Transmitted Wave Heights Measured One-Half Wavelength Behind Breakwater for Stone Subjected to Breaking Waves; $W_a = 0.55$ lb; $\gamma_a = 167$ pcf; Cot $\alpha = 1.5$ and 2.0

					Transmitted Wave Height, ft						
T, sec	H, ft	d, ft	d/L	H/H_D	Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
					Test Series 1; Cot α = 1.5						
1.18	0.38	0.55	0.12	1.00	0.009	0.009	0.009	0.009	0.009	0.009	0.000
1.24	0.45	0.60	0.12	1.18	0.012	0.012	0.012	0.012	0.012	0.012	0.000
1.29	0.51	0.65	0.12	1.34	0.017	0.016	0.017	0.016	0.017	0.017	0.001
1.34	0.55	0.70	0.12	1.45	0.023	0.022	0.022	0.022	0.022	0.022	0.001
1.62	0.58	0.75	0.10	1.53	0.035	0.037	0.036	0.037	0.035	0.036	0.001
					Test Series 2; Cot α = 1.5						
1.45	0.37	0.40	0.08	1.00	0.009	0.009	0.008	0.009	0.008	0.009	0.001
1.90	0.42	0.40	0.06	1.14	0.010	0.010	0.010	0.011	0.011	0.010	0.001
2.02	0.46	0.45	0.06	1.24	0.014	0.013	0.013	0.013	0.014	0.013	0.001
1.70	0.54	0.55	0.08	1.46	0.019	0.018	0.019	0.019	0.018	0.019	0.001
2.32	0.58	0.60	0.06	1.57	0.024	0.025	0.025	0.026	0.025	0.025	0.001
1.85	0.60	0.65	0.08	1.62	0.035	0.037	0.037	0.038	0.036	0.037	0.001
					Test Series 3; Cot α = 2.0						
1.24	0.45	0.60	0.12	1.00	0.009	0.009	0.009	0.008	0.009	0.009	0.001
1.29	0.51	0.65	0.12	1.13	0.011	0.011	0.011	0.011	0.011	0.011	0.000
1.34	0.55	0.70	0.12	1.22	0.014	0.015	0.015	0.015	0.014	0.015	0.001
1.47	0.63	0.85	0.12	1.40	0.030	0.031	0.031	0.028	0.030	0.030	0.001
1.56	0.66	0.95	0.12	1.47	0.041	0.042	0.039	0.038	0.041	0.040	0.002
					Test Series 4; Cot α = 2.0						
2.82	0.42	0.40	0.04	1.00	0.011	0.012	0.011	0.012	0.011	0.011	0.001
2.02	0.46	0.45	0.06	1.10	0.013	0.012	0.012	0.012	0.013	0.012	0.001
1.70	0.54	0.55	0.08	1.29	0.015	0.016	0.015	0.014	0.015	0.015	0.001
2.32	0.58	0.60	0.06	1.38	0.024	0.024	0.023	0.024	0.024	0.024	0.001
1.85	0.60	0.65	0.08	1.43	0.030	0.029	0.032	0.031	0.030	0.030	0.001
1.67	0.66	0.80	0.10	1.57	0.043	0.041	0.043	0.042	0.044	0.043	0.001

Table 10

Transmitted Wave Heights Measured One Wavelength Behind Breakwater for Stone Subjected to Breaking Waves; $W_a = 0.55$ lb; $\gamma_a = 167$ pcf; Cot $\alpha = 1.5$ and 2.0

					Transmitted Wave Height, ft						
T, sec	H, ft	d, ft	d/L	H/H_D	Test 1	Test 2	Test 3	Test 4	Test 5	Average	Standard Deviation
					Test Series 1; Cot α = 1.5						
1.18	0.38	0.55	0.12	1.00	0.009	0.009	0.009	0.009	0.009	0.009	0.000
1.24	0.45	0.60	0.12	1.18	0.011	0.011	0.010	0.010	0.011	0.011	0.001
1.29	0.51	0.65	0.12	1.34	0.015	0.015	0.016	0.015	0.015	0.015	0.001
1.34	0.55	0.70	0.12	1.45	0.022	0.022	0.021	0.021	0.022	0.022	0.001
1.62	0.58	0.75	0.10	1.53	0.034	0.033	0.036	0.033	0.035	0.034	0.001
					Test Series 2; Cot α = 1.5						
1.45	0.37	0.40	0.08	1.00	0.008	0.009	0.008	0.009	0.009	0.009	0.001
1.90	0.42	0.40	0.06	1.14	0.009	0.010	0.010	0.009	0.010	0.010	0.001
2.02	0.46	0.45	0.06	1.24	0.014	0.013	0.014	0.014	0.014	0.014	0.001
1.70	0.54	0.55	0.08	1.46	0.017	0.018	0.018	0.018	0.019	0.018	0.001
2.32	0.58	0.60	0.06	1.57	0.028	0.026	0.027	0.027	0.027	0.027	0.001
1.85	0.60	0.65	0.08	1.62	0.033	0.034	0.033	0.033	0.034	0.033	0.001
					Test Series 3; Cot α = 2.0						
1.24	0.45	0.60	0.12	1.00	0.009	0.009	0.008	0.008	0.009	0.009	0.001
1.29	0.51	0.65	0.12	1.13	0.010	0.010	0.009	0.010	0.010	0.010	0.001
1.34	0.55	0.70	0.12	1.22	0.014	0.014	0.014	0.015	0.014	0.014	0.001
1.47	0.63	0.85	0.12	1.40	0.027	0.029	0.030	0.027	0.028	0.028	0.001
1.56	0.66	0.95	0.12	1.47	0.039	0.042	0.040	0.042	0.041	0.041	0.001
					Test Series 4; Cot α = 2.0						
2.82	0.42	0.40	0.04	1.00	0.012	0.011	0.012	0.011	0.011	0.011	0.001
2.02	0.46	0.45	0.06	1.10	0.012	0.012	0.013	0.013	0.012	0.012	0.001
1.70	0.54	0.55	0.08	1.29	0.016	0.017	0.017	0.016	0.015	0.016	0.001
2.32	0.58	0.60	0.06	1.38	0.024	0.023	0.023	0.024	0.022	0.023	0.001
1.85	0.60	0.65	0.08	1.43	0.027	0.029	0.028	0.029	0.027	0.028	0.001
1.67	0.66	0.80	0.10	1.57	0.041	0.039	0.042	0.040	0.042	0.041	0.001

Table 11

Relative Transmitted Wave Heights for Dolosse Subjected to Nonbreaking Waves; $W_a = 0.276$ lb; $\gamma_a = 142.2$ pcf; d = 2.0 ft; Cot α = 1.5 and 2.0

				Transmitted and Relative Transmitted Wave Heights			
				Measured at L/2*		Measured at L*	
T , sec	d/L	H , ft	H/H_D	H_t , ft	H_t/H_{t_D}	H_t , ft	H_t/H_{t_D}
			Test Series 1; Cot α = 1.5				
1.31	0.25	0.57	1.00	0.008	1.00	0.008	1.00
1.31	0.25	0.63	1.10	0.009	1.13	0.008	1.00
1.31	0.25	0.68	1.20	0.012	1.50	0.012	1.50
1.31	0.25	0.74	1.30	0.013	1.63	0.012	1.50
			Test Series 2; Cot α = 1.5				
1.89	0.15	0.57	1.00	0.017	1.00	0.017	1.00
1.89	0.15	0.63	1.10	0.018	1.06	0.018	1.06
1.89	0.15	0.68	1.20	0.023	1.35	0.022	1.29
1.89	0.15	0.74	1.30	0.044	2.59	0.038	2.24
			Test Series 3; Cot α = 1.5				
2.65	0.10	0.57	1.00	0.019	1.00	0.020	1.00
2.65	0.10	0.63	1.10	0.020	1.05	0.021	1.05
2.65	0.10	0.68	1.20	0.027	1.42	0.027	1.35
2.65	0.10	0.74	1.30	0.040	2.11	0.038	1.90
2.65	0.10	0.80	1.40	0.054	2.84	0.051	2.55
			Test Series 4; Cot α = 2.0				
1.31	0.25	0.63	1.00	0.006	1.00	0.005	1.00
1.31	0.25	0.69	1.10	0.007	1.17	0.006	1.20
1.31	0.25	0.76	1.20	0.009	1.50	0.008	1.60
			Test Series 5; Cot α = 2.0				
1.89	0.15	0.63	1.00	0.012	1.00	0.011	1.00
1.89	0.15	0.69	1.10	0.014	1.17	0.013	1.18
1.89	0.15	0.76	1.20	0.022	1.83	0.017	1.55
1.89	0.15	0.82	1.30	0.031	2.58	0.026	2.36
1.89	0.15	0.88	1.40	0.042	3.50	0.036	3.27
			Test Series 6; Cot α = 2.0				
2.65	0.10	0.63	1.00	0.014	1.00	0.014	1.00
2.65	0.10	0.69	1.10	0.015	1.07	0.014	1.00
2.65	0.10	0.76	1.20	0.017	1.21	0.017	1.21
2.65	0.10	0.82	1.30	0.023	1.64	0.023	1.64

* Distance in wavelengths behind center line of breakwater.

Table 12

Relative Transmitted Wave Heights for Dolosse Subjected to Breaking Waves;
$W_a = 0.276$ lb; $\gamma_a = 142.2$ pcf; Cot α = 1.5 and 2.0

					Transmitted and Relative Transmitted Wave Heights			
					Measured at L/2*		Measured at L*	
T, sec	H, ft	d, ft	d/L	H/H_D	H_t, ft	H_t/H_{t_D}	H_t, ft	H_t/H_{t_D}
			Test Series 1; Cot α = 1.5					
1.62	0.45	0.50	0.08	1.00	0.007	1.00	0.007	1.00
1.45	0.52	0.60	0.10	1.16	0.007	1.00	0.007	1.00
1.85	0.60	0.65	0.08	1.33	0.014	2.00	0.014	2.00
1.67	0.66	0.80	0.10	1.47	0.028	4.00	0.028	4.00
			Test Series 2; Cot α = 1.5					
2.02	0.46	0.45	0.06	1.00	0.006	1.00	0.006	1.00
1.29	0.51	0.65	0.12	1.11	0.007	1.17	0.008	1.33
1.34	0.55	0.70	0.12	1.20	0.009	1.50	0.009	1.50
1.37	0.61	0.95	0.14	1.33	0.018	3.00	0.017	2.83
1.52	0.64	0.90	0.12	1.39	0.024	4.00	0.023	3.83
1.56	0.66	0.95	0.12	1.43	0.029	4.83	0.028	4.67
1.73	0.71	0.85	0.10	1.54	0.031	5.17	0.030	5.00
			Test Series 3; Cot α = 2.0					
1.30	0.56	0.85	0.14	1.00	0.007	1.00	0.007	1.00
1.47	0.63	0.85	0.12	1.13	0.008	1.14	0.009	1.29
1.56	0.66	0.95	0.12	1.18	0.013	1.86	0.013	1.86
1.73	0.71	0.85	0.10	1.27	0.011	1.57	0.011	1.57
1.78	0.77	0.90	0.10	1.38	0.017	2.43	0.017	2.43
			Test Series 4; Cot α = 2.0					
1.70	0.54	0.55	0.08	1.00	0.005	1.00	0.004	1.00
1.85	0.60	0.65	0.08	1.11	0.006	1.20	0.007	1.75
1.99	0.70	0.75	0.08	1.30	0.009	1.80	0.010	2.50
1.78	0.77	0.90	0.10	1.43	0.013	2.60	0.013	3.25

* Distance in wavelengths behind center line of breakwater.

Table 13

Relative Transmitted Wave Heights for Stone Subjected to Breaking Waves; W_a = 0.55 lb; γ_a = 167 pcf; Cot α = 1.5 and 2.0

T, sec	H, ft	d, ft	d/L	H/H_D	Transmitted and Relative Transmitted Wave Heights: Measured at L/2* H_t, ft	Measured at L/2* H_t/H_{t_D}	Measured at L* H_t, ft	Measured at L* H_t/H_{t_D}
			Test Series 1; Cot α = 1.5					
1.18	0.38	0.55	0.12	1.00	0.009	1.00	0.009	1.00
1.24	0.45	0.60	0.12	1.18	0.012	1.33	0.011	1.22
1.29	0.51	0.65	0.12	1.34	0.017	1.89	0.015	1.67
1.34	0.55	0.70	0.12	1.45	0.022	2.44	0.022	2.44
1.62	0.58	0.75	0.10	1.53	0.036	4.00	0.034	3.78
			Test Series 2; Cot α = 1.5					
1.45	0.37	0.40	0.08	1.00	0.009	1.00	0.009	1.00
1.90	0.42	0.40	0.06	1.14	0.010	1.11	0.010	1.11
2.02	0.46	0.45	0.06	1.24	0.013	1.44	0.014	1.56
1.70	0.54	0.55	0.08	1.46	0.019	2.11	0.018	2.00
2.32	0.58	0.60	0.06	1.57	0.025	2.78	0.027	3.00
1.85	0.60	0.65	0.08	1.62	0.037	4.11	0.033	3.67
			Test Series 3; Cot α = 2.0					
1.24	0.45	0.60	0.12	1.00	0.009	1.00	0.009	1.00
1.29	0.51	0.65	0.12	1.13	0.011	1.22	0.010	1.11
1.34	0.55	0.70	0.12	1.22	0.015	1.67	0.014	1.56
1.47	0.63	0.85	0.12	1.40	0.030	3.33	0.028	3.11
1.56	0.66	0.95	0.12	1.47	0.040	4.44	0.041	4.56
			Test Series 4; Cot α = 2.0					
2.82	0.42	0.40	0.04	1.00	0.011	1.00	0.011	1.00
2.02	0.46	0.45	0.06	1.10	0.012	1.09	0.012	1.09
1.70	0.54	0.55	0.08	1.29	0.015	1.36	0.016	1.45
2.32	0.58	0.60	0.06	1.38	0.024	2.18	0.023	2.09
1.85	0.60	0.65	0.08	1.43	0.030	2.73	0.028	2.55
1.67	0.66	0.80	0.10	1.57	0.043	3.91	0.041	3.73

* Distance in wavelengths behind center line of breakwater.

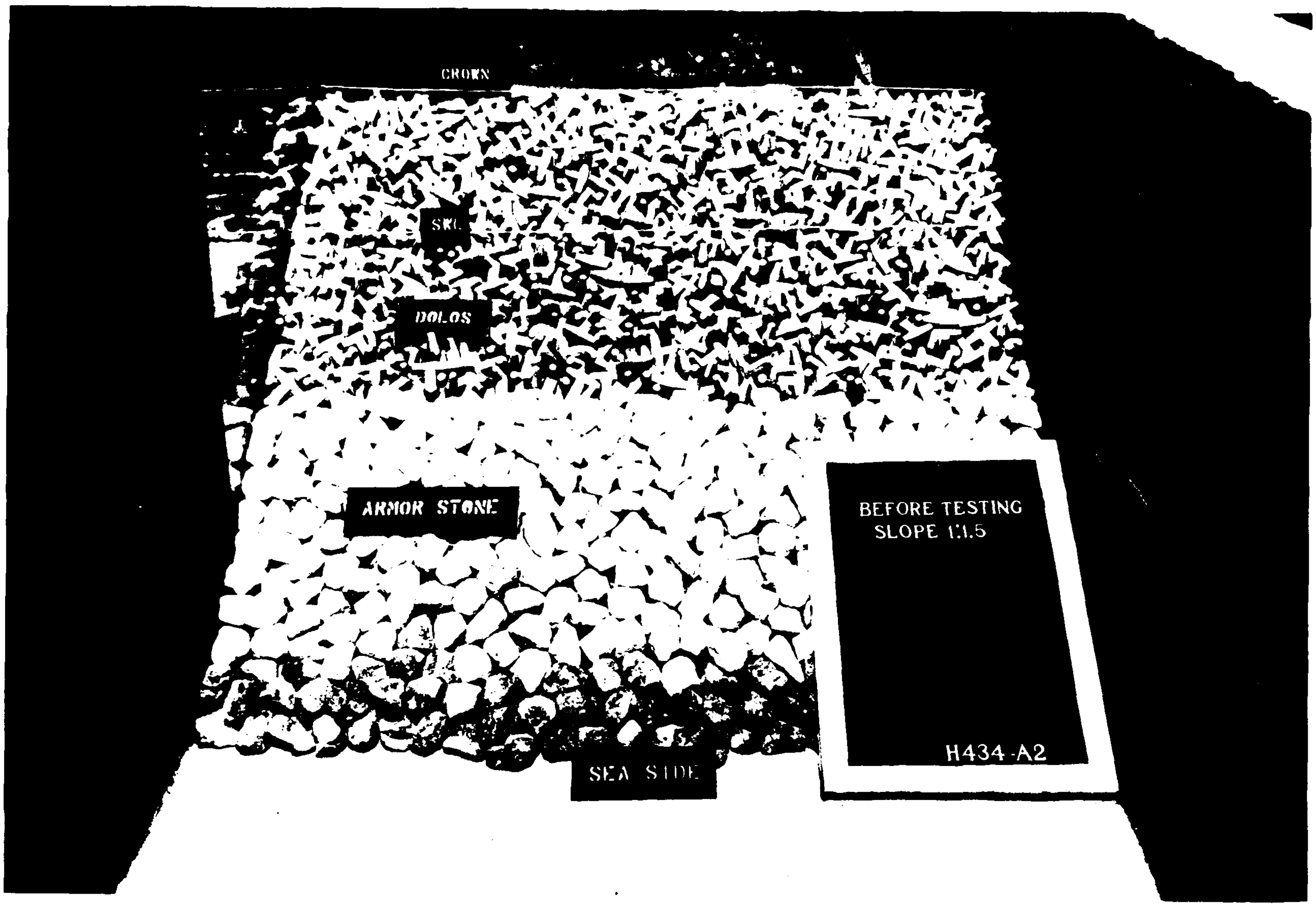


Photo 1. Sea-side view of 5-ft dolos section before wave attack at a 1V on 1.5H sea-side structure slope

Table 14

Summary of Relative Transmitted Wave Heights

Armor Type	Wave Form	Cot α	H/H_D	H_t/H_{t_D}
Dolos	Nonbreaking	1.5	1.00	1.0
		1.5	1.10	1.2
		1.5	1.20	1.5
		1.5	1.30	2.6
		1.5	1.40	2.8
		2.0	1.00	1.0
		2.0	1.10	1.2
		2.0	1.20	1.8
		2.0	1.30	2.6
		2.0	1.40	3.5
Dolos	Breaking	1.5	1.00	1.0
		1.5	1.10	1.3
		1.5	1.20	1.7
		1.5	1.30	2.5
		1.5	1.40	4.3
		1.5	1.50	5.1
		2.0	1.00	1.0
		2.0	1.10	1.7
		2.0	1.20	2.0
		2.0	1.30	2.5
		2.0	1.40	3.1
Stone	Breaking	1.5	1.00	1.0
		1.5	1.10	1.2
		1.5	1.20	1.4
		1.5	1.30	1.7
		1.5	1.40	2.1
		1.5	1.50	3.4
		1.5	1.60	4.1
		2.0	1.00	1.0
		2.0	1.10	1.1
		2.0	1.20	1.6
		2.0	1.30	2.4
		2.0	1.40	3.4
		2.0	1.50	4.7

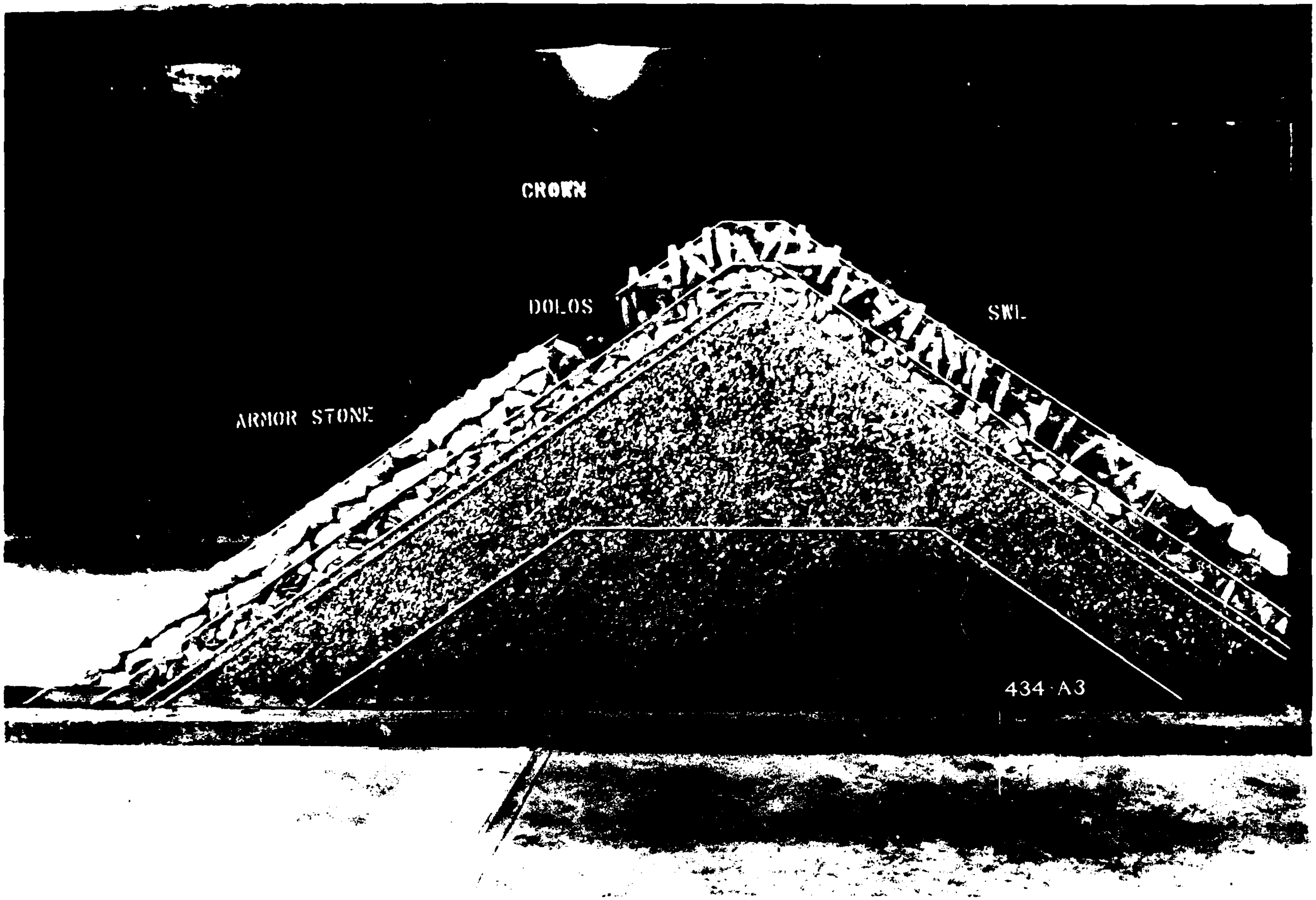


Photo 2. End view of 5-ft dolos section before wave attack at a 1V on 1.5H sea-side structure slope

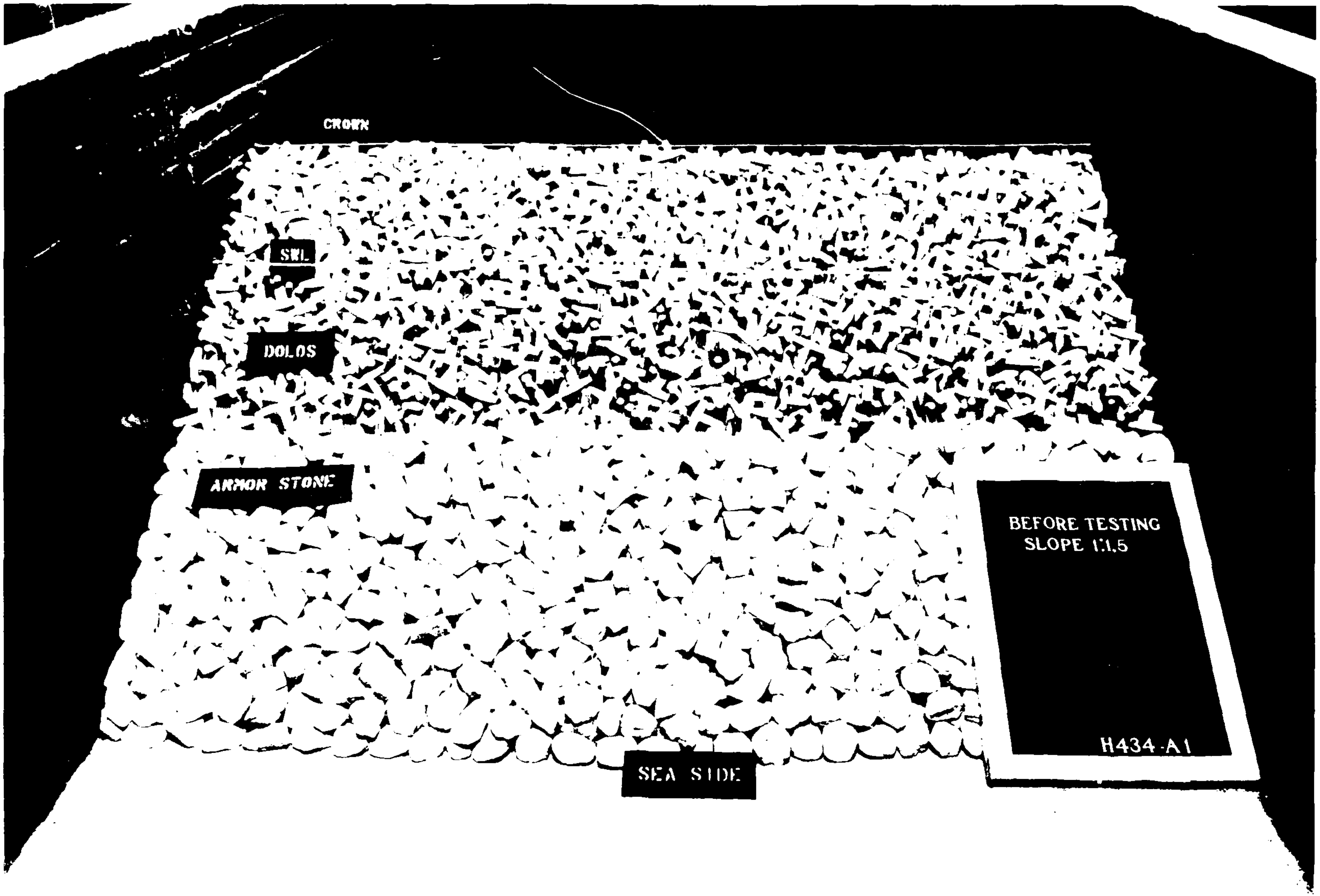


Photo 3. Sea-side view of 6.75-ft dolos section before wave attack at a 1V on 1.5H sea-side structure slope

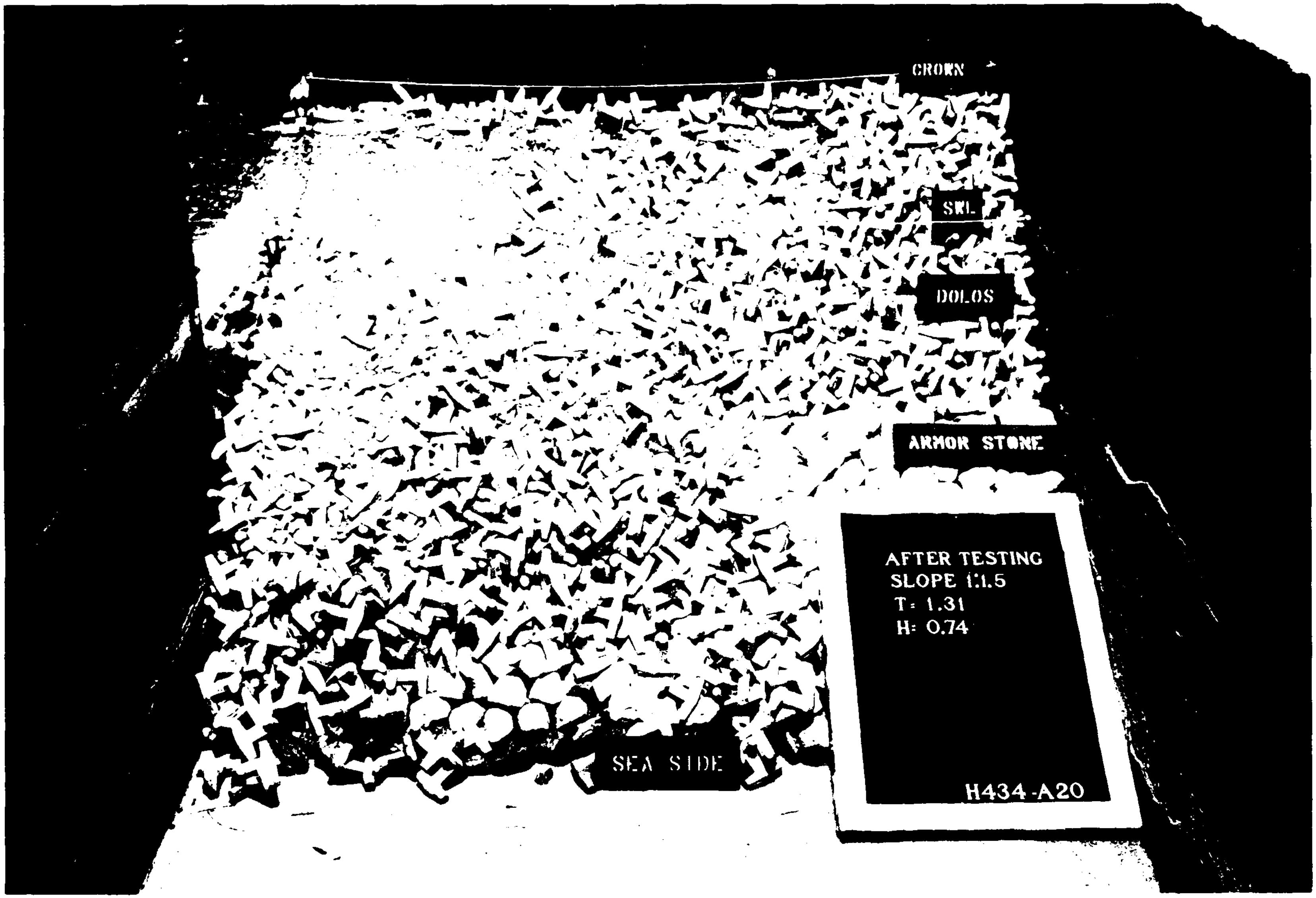


Photo 4. Sea-side view of 5-ft dolos section after completion of test series 1 of the nonbreaking wave tests

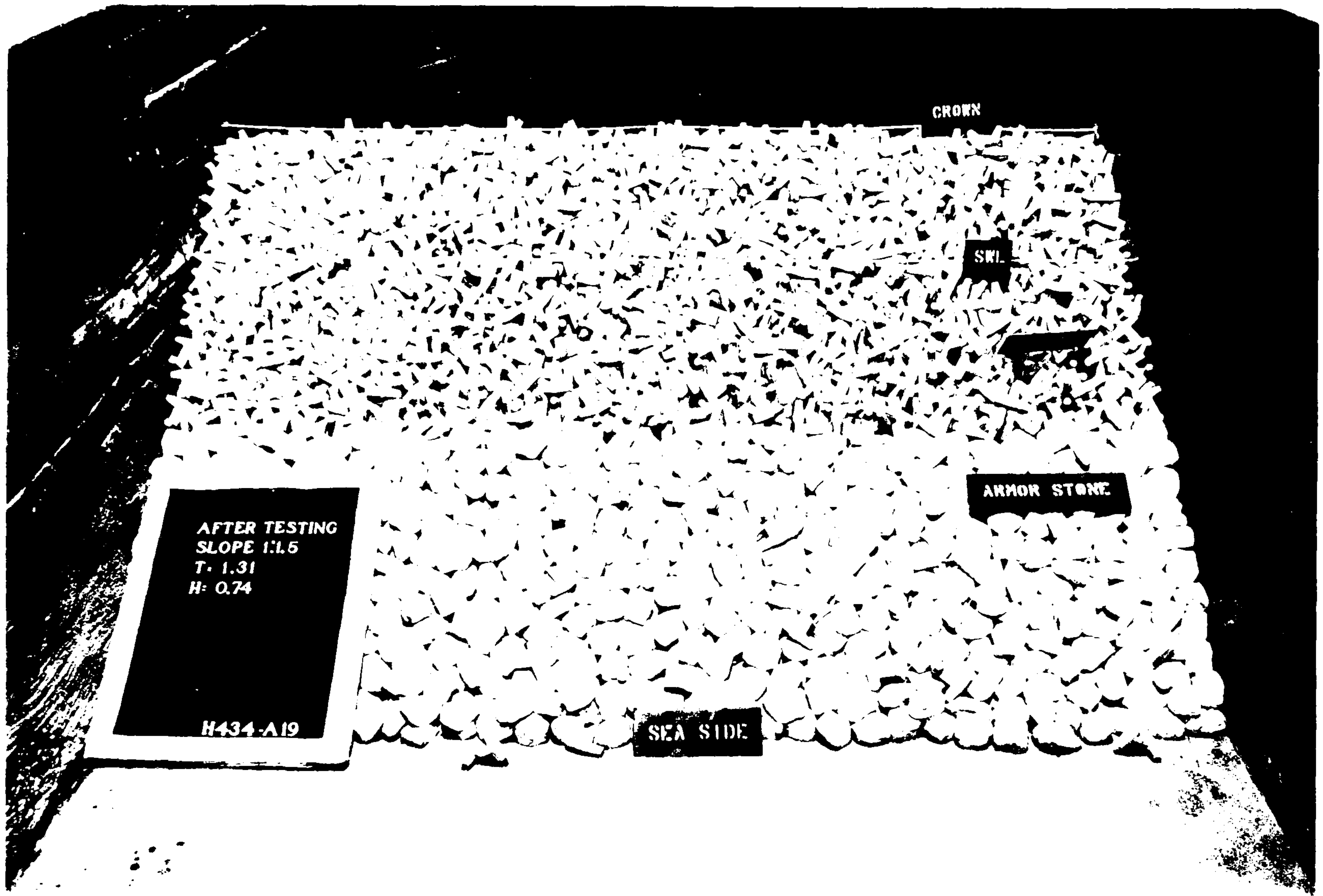


Photo 5. Sea-side view of 6.75-ft dolos section after completion of test series 1 of the nonbreaking wave tests

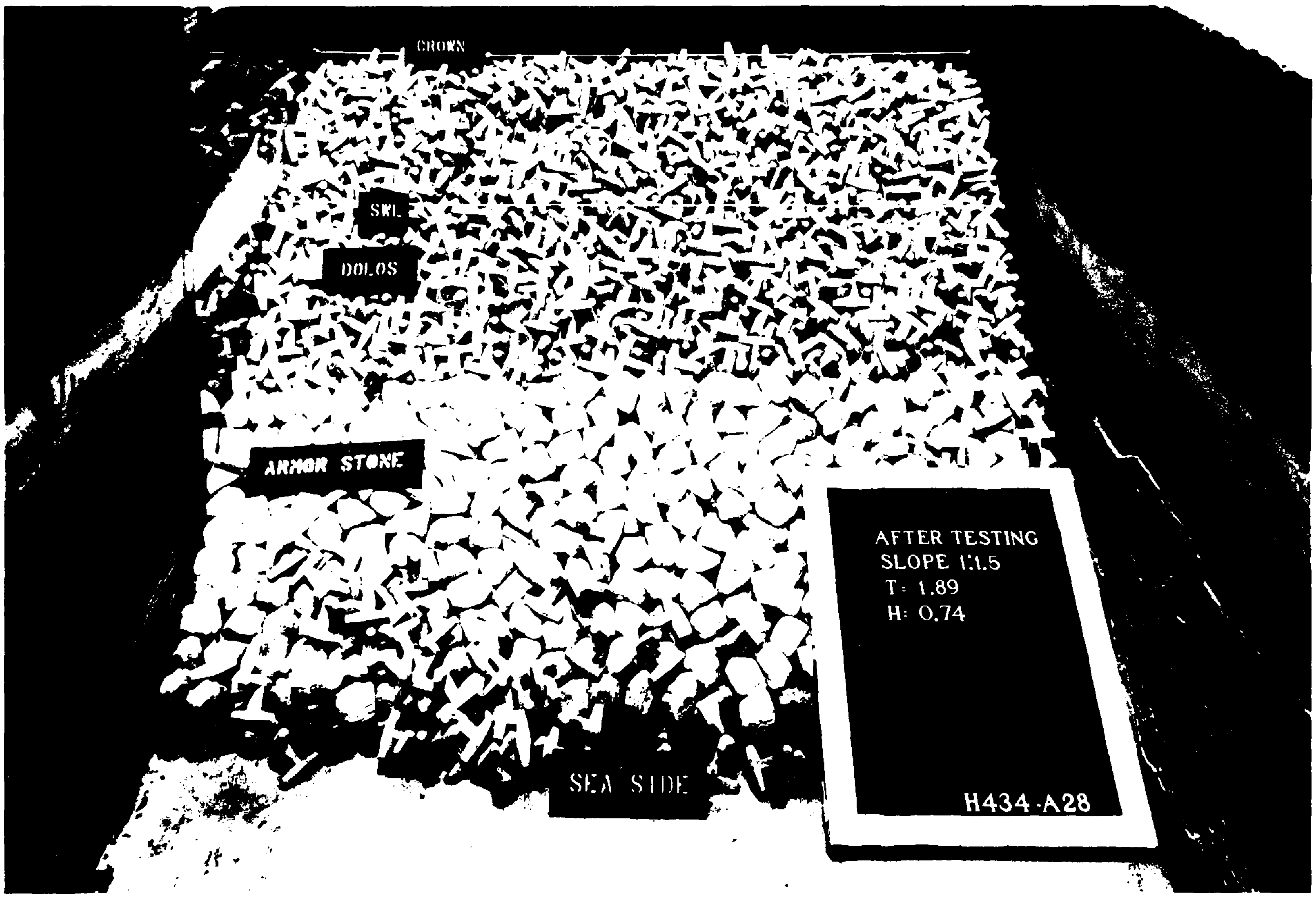


Photo 6. Sea-side view of 5-ft dolos section after completion of test series 2 of the nonbreaking wave tests

Photo 7. Sea-side view of 6.75-ft dolos section after completion of test series 2 of the nonbreaking wave tests

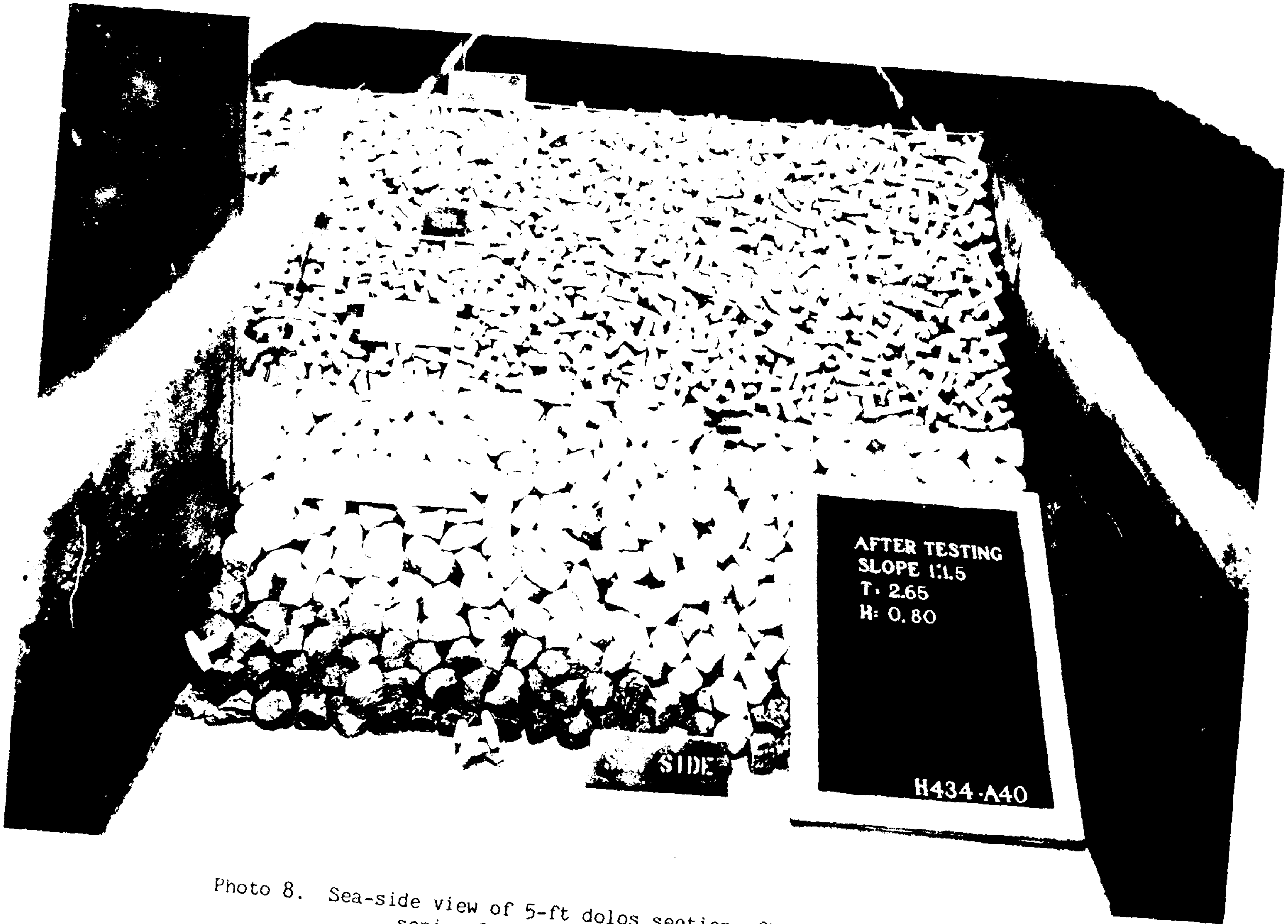


Photo 8. Sea-side view of 5-ft dolos section after completion of test series 3 of the nonbreaking wave tests

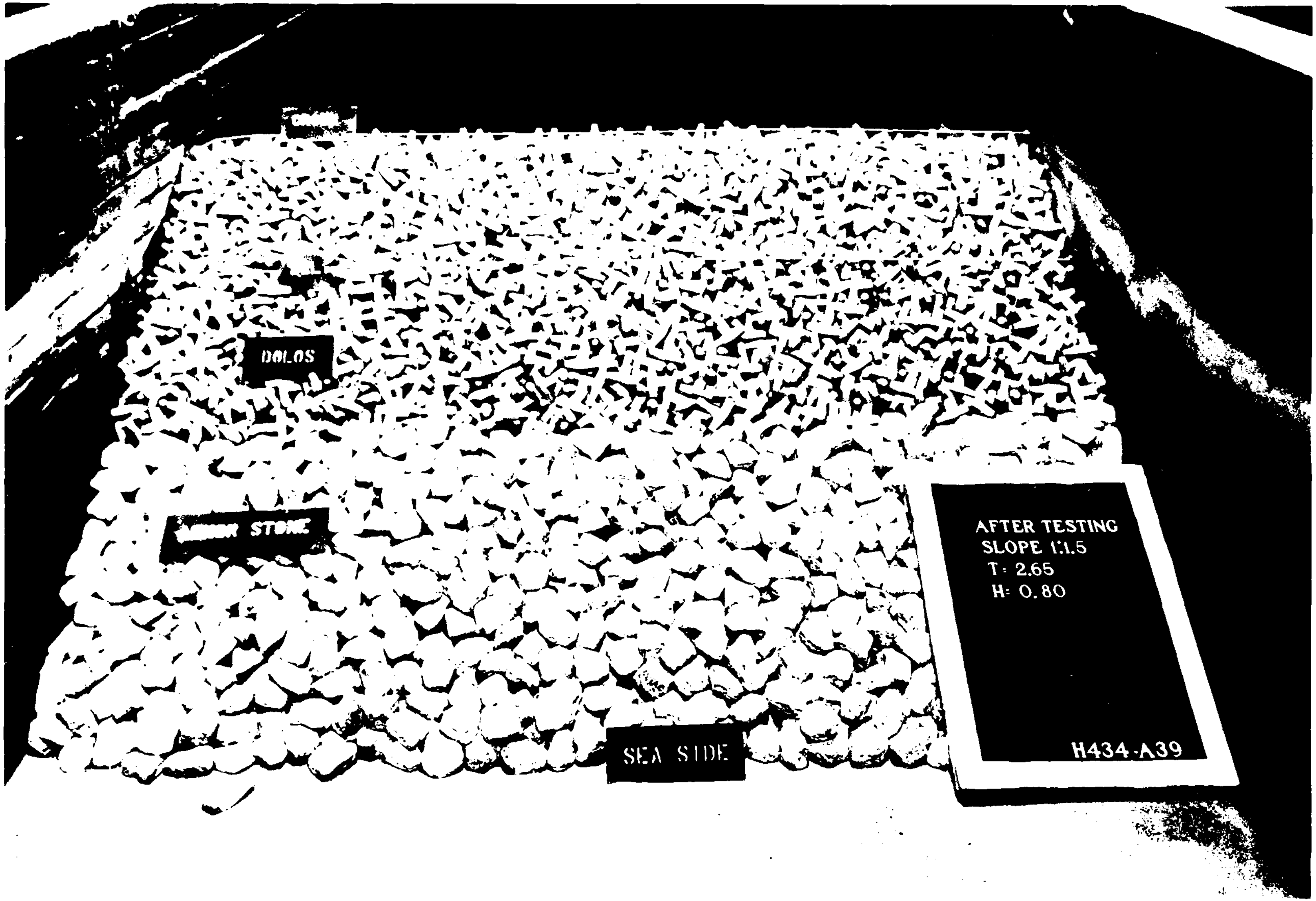


Photo 9. Sea-side view of 6.75-ft dolos section after completion of test series 3 of the nonbreaking wave tests

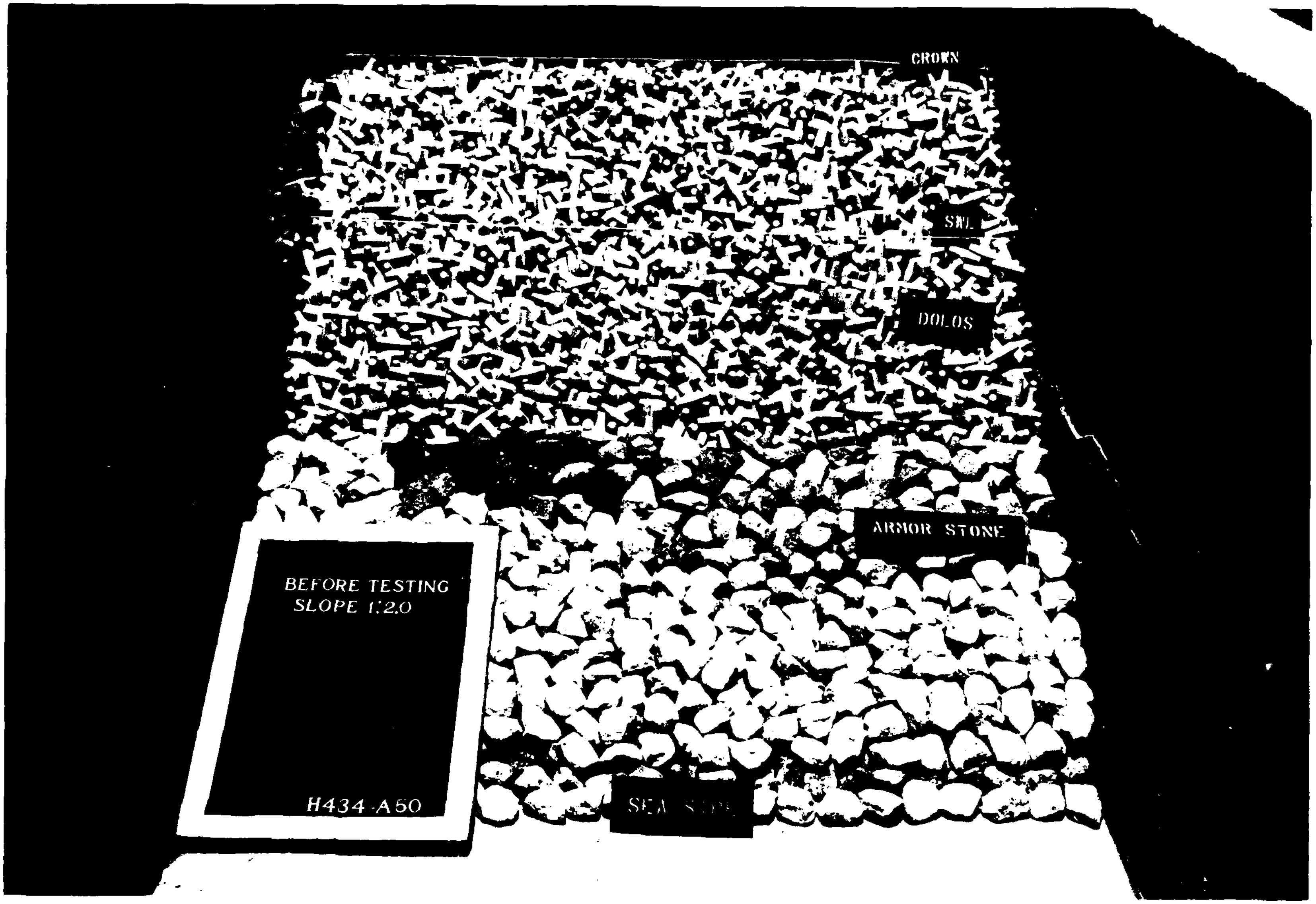


Photo 10. Sea-side view of 5-ft dolos section before wave attack at a 1V on 2H sea-side structure slope

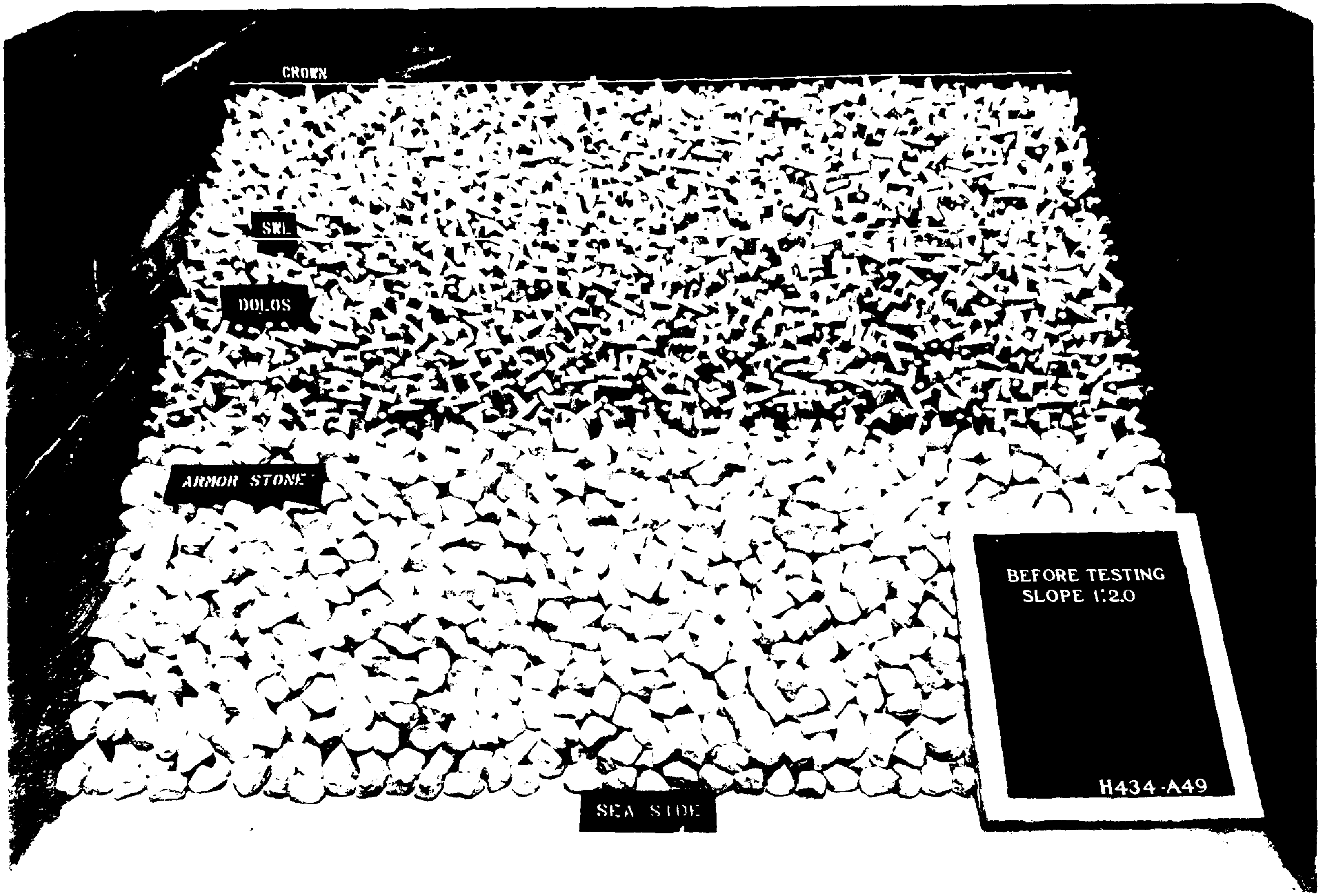


Photo 11. Sea-side view of 6.75-ft dolos section before wave attack at a 1V on 2H sea-side structure slope

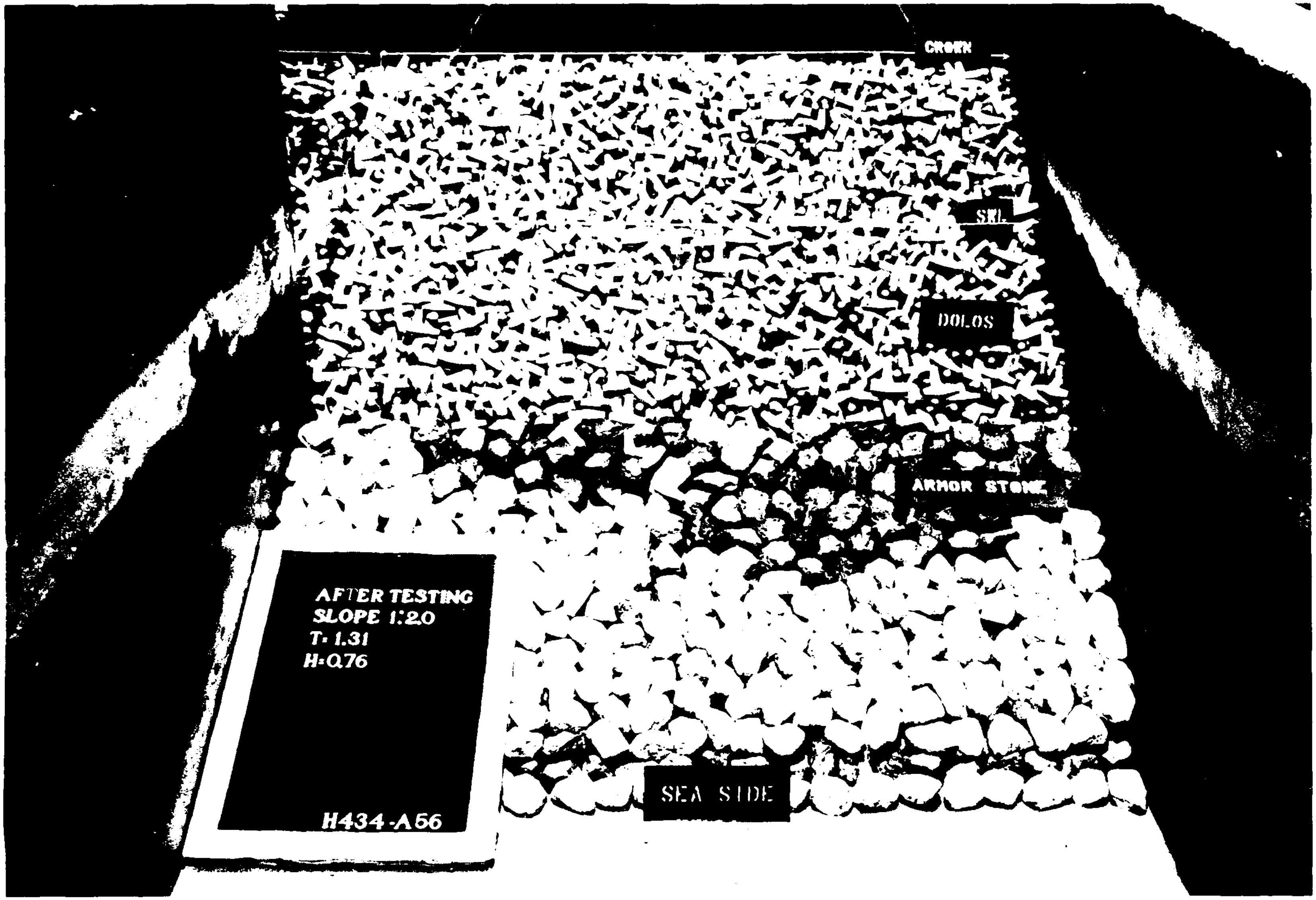


Photo 12. Sea-side view of 5-ft dolos section after completion of test series 4 of the nonbreaking wave tests

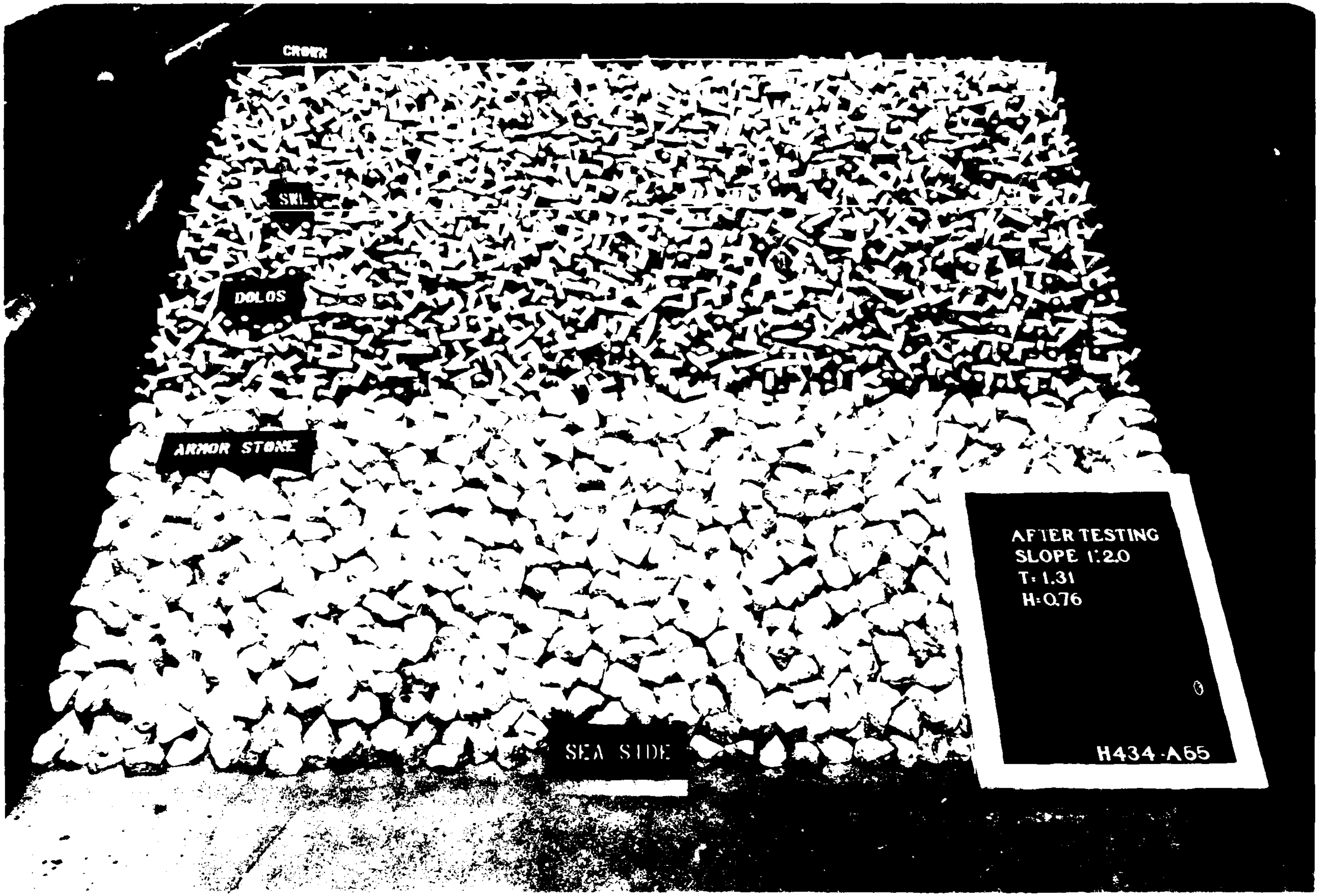


Photo 13. Sea-side view of 6.75-ft dolos section after completion of test series 4 of the nonbreaking wave tests

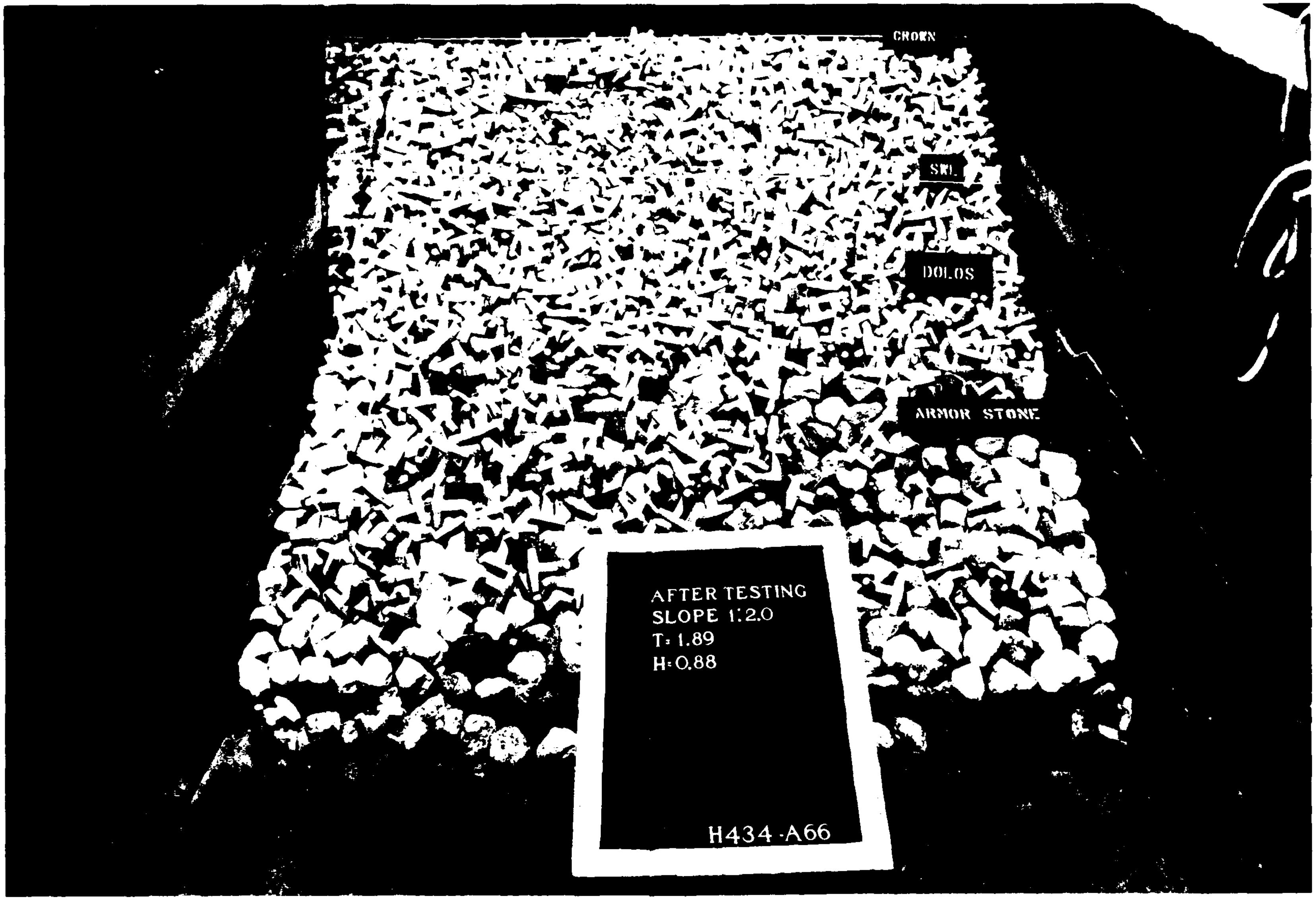


Photo 14. Sea-side view of 5-ft dolos section after completion of test series 5 of the nonbreaking wave tests

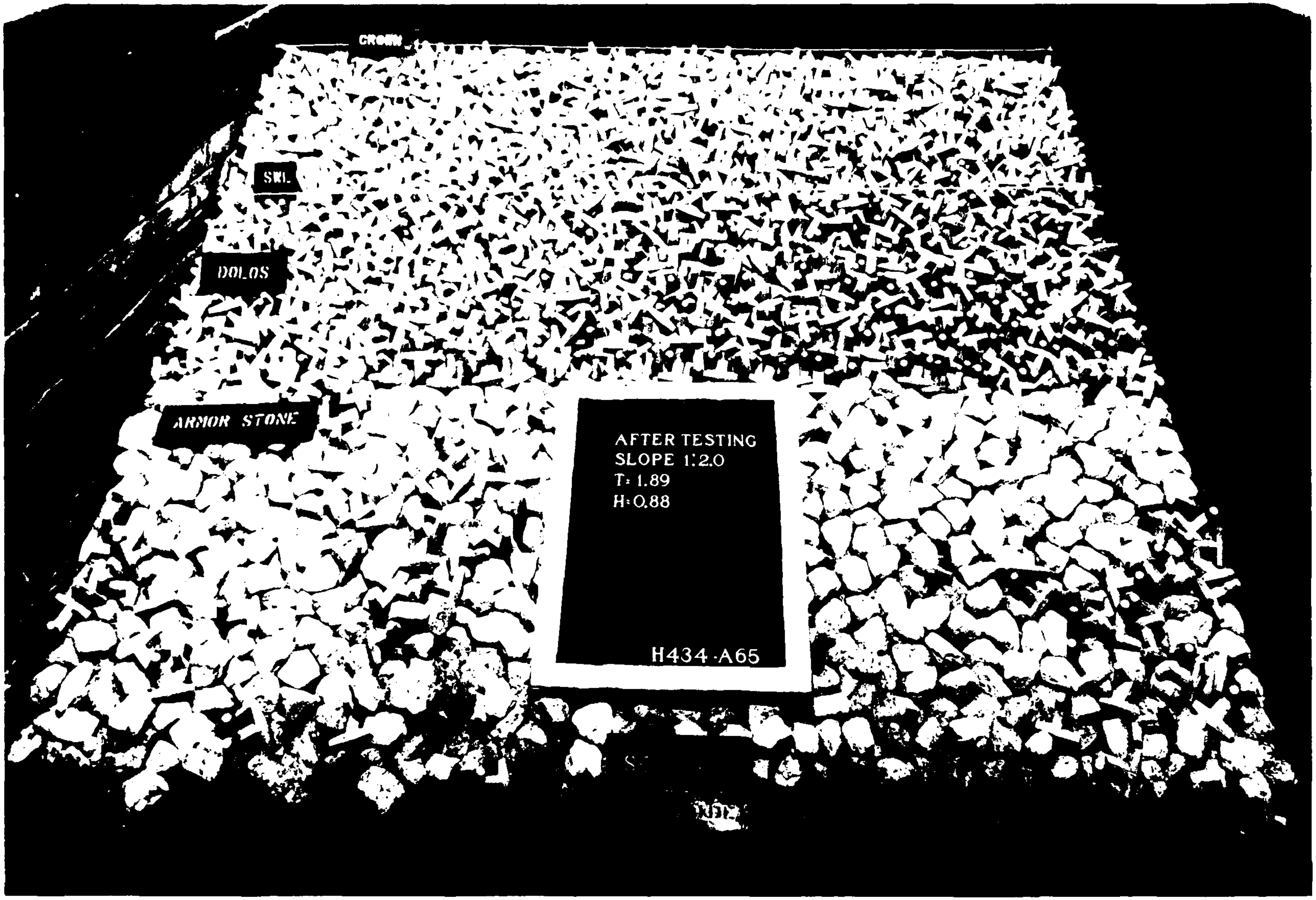


Photo 15. Sea-side view of 6.75-ft dolos section after completion of test series 5 of the nonbreaking wave tests

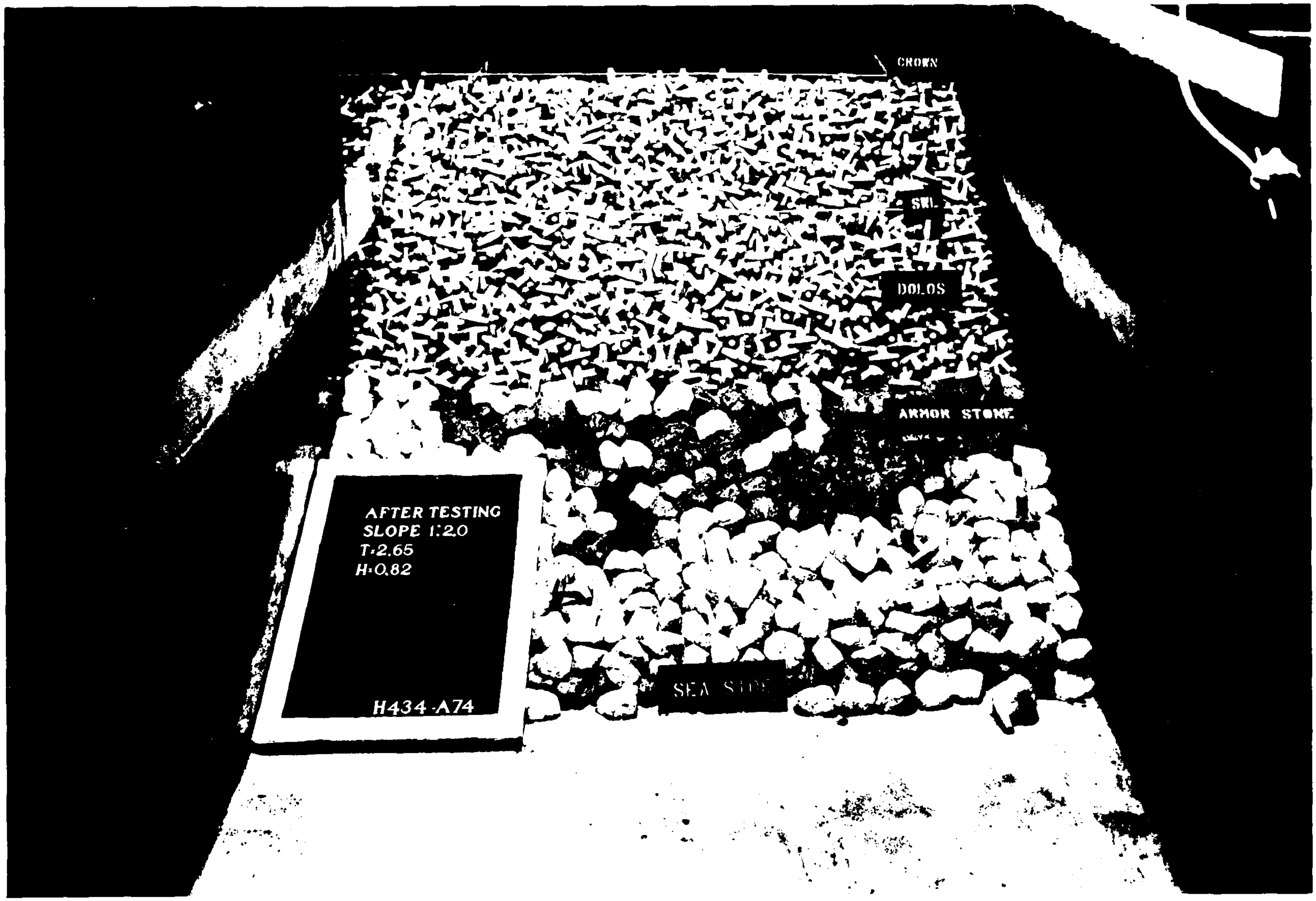


Photo 16. Sea-side view of 5-ft dolos section after completion of test series 6 of the nonbreaking wave tests

Photo 17. Sea-side view of 6.75-ft dolos section after completion of test series 6 of the nonbreaking wave tests

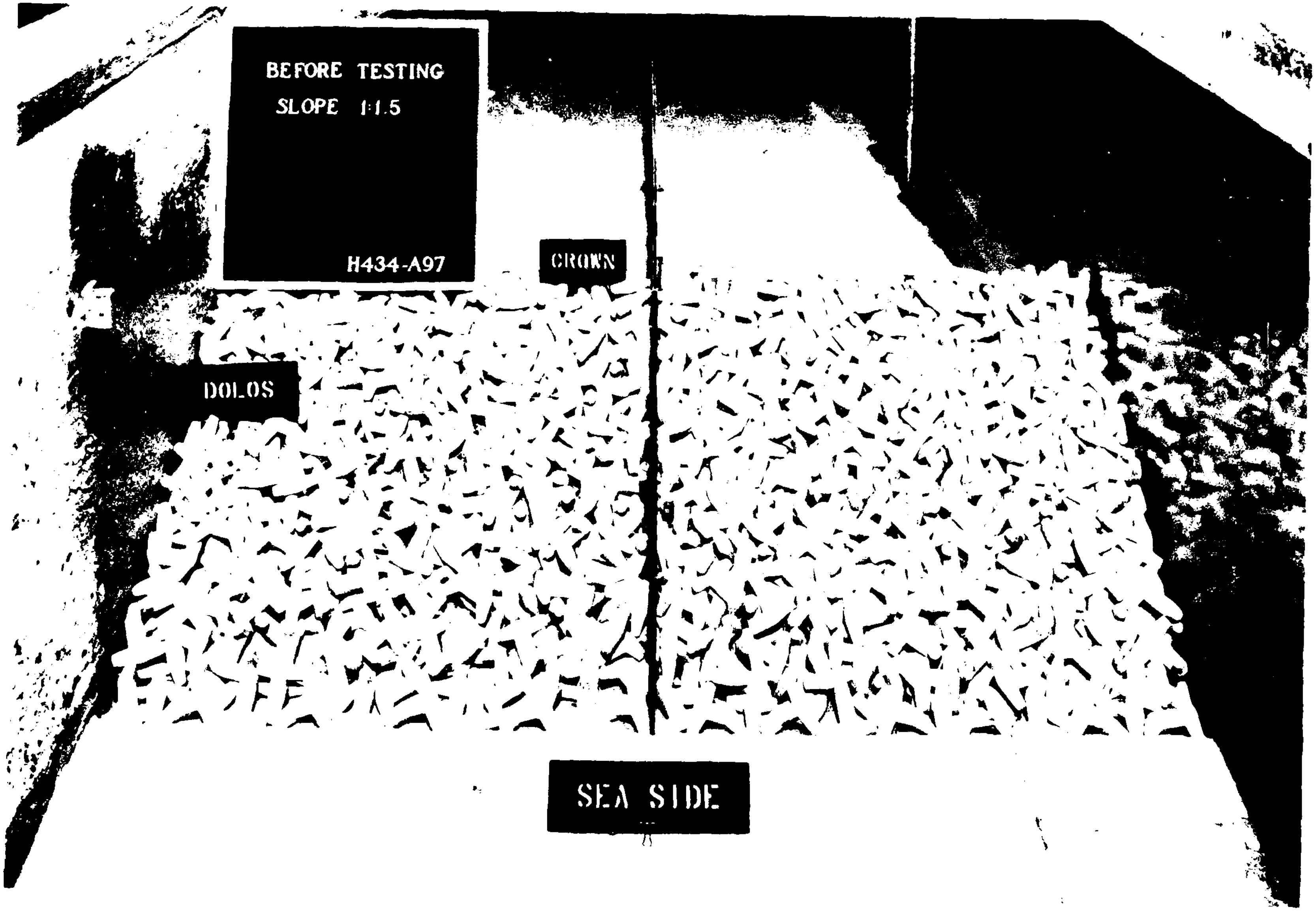


Photo 18. Sea-side view of 2.5-ft dolos sections before wave attack at a 1V on 1.5H sea-side structure slope

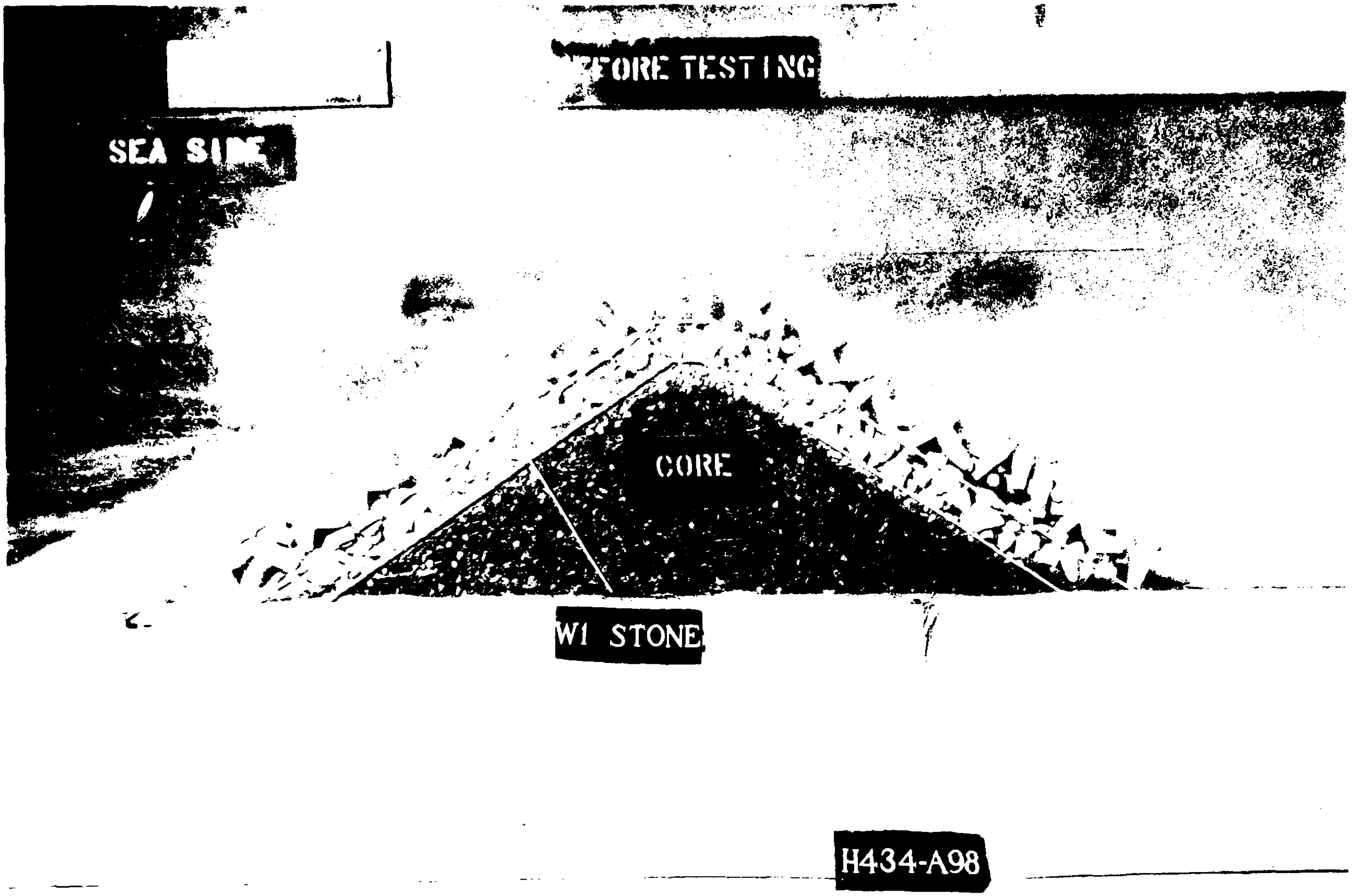


Photo 19. End view of 2.5-ft dolos sections before wave attack at a 1V on 1.5H sea-side structure slope

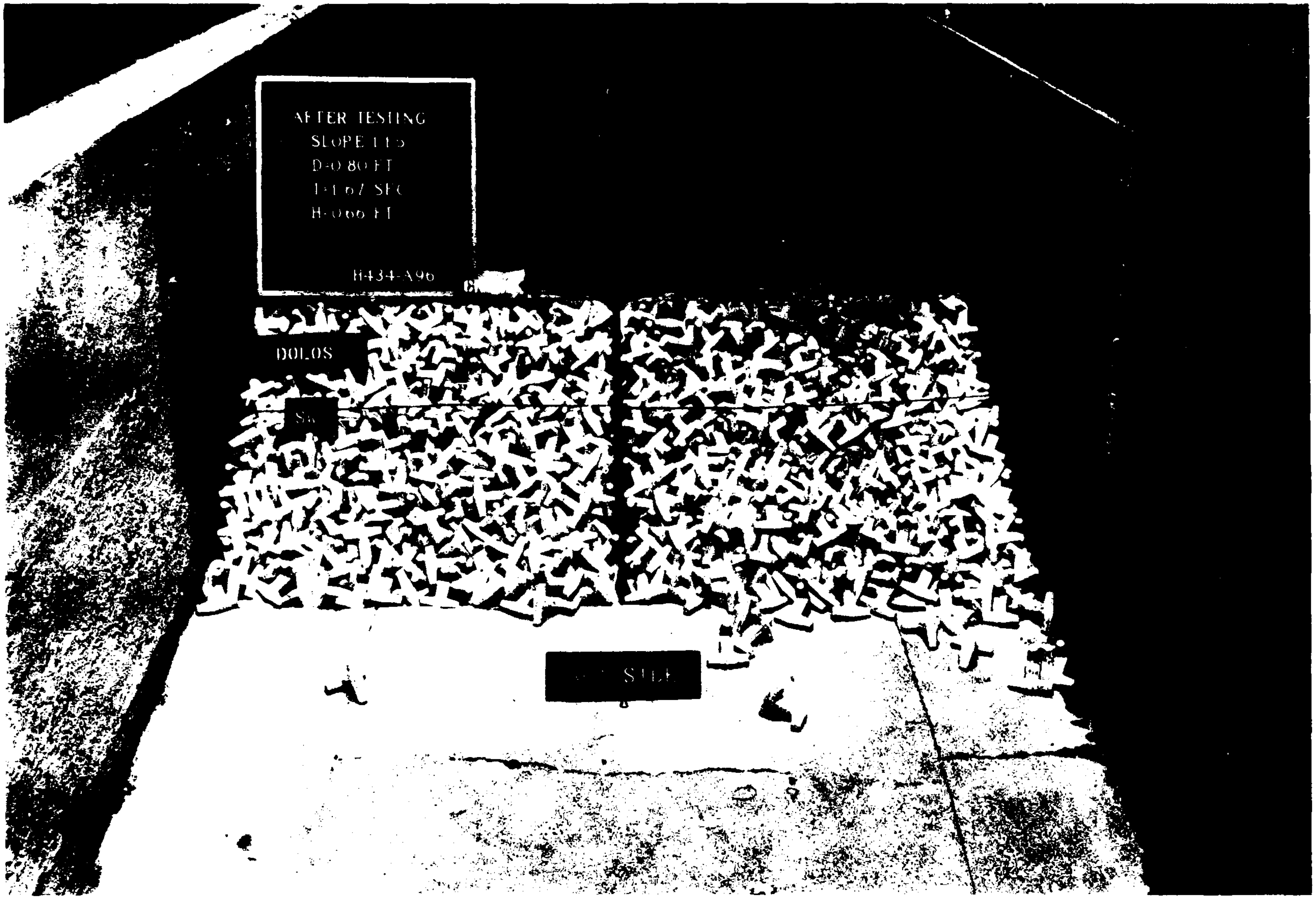


Photo 20. Sea-side view of 2.5-ft dolos sections after completion of test series 1 of the breaking wave test

Photo 21. Sea-side view of 2.5-ft dolos sections after completion of test series 2 of the breaking wave tests

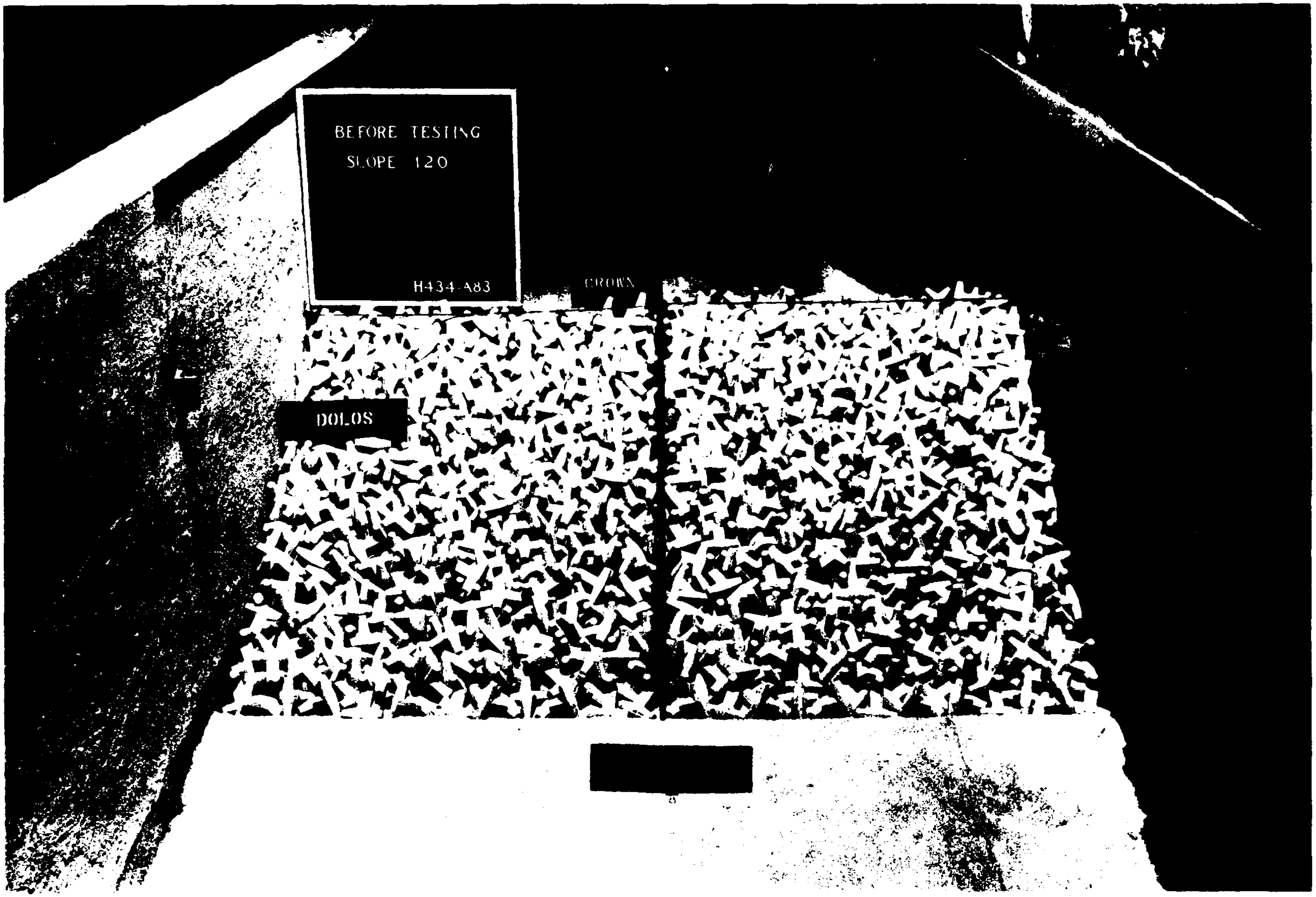


Photo 22. Sea-side view of 2.5-ft dolos sections before wave attack at a 1V on 2H sea-side structure slope

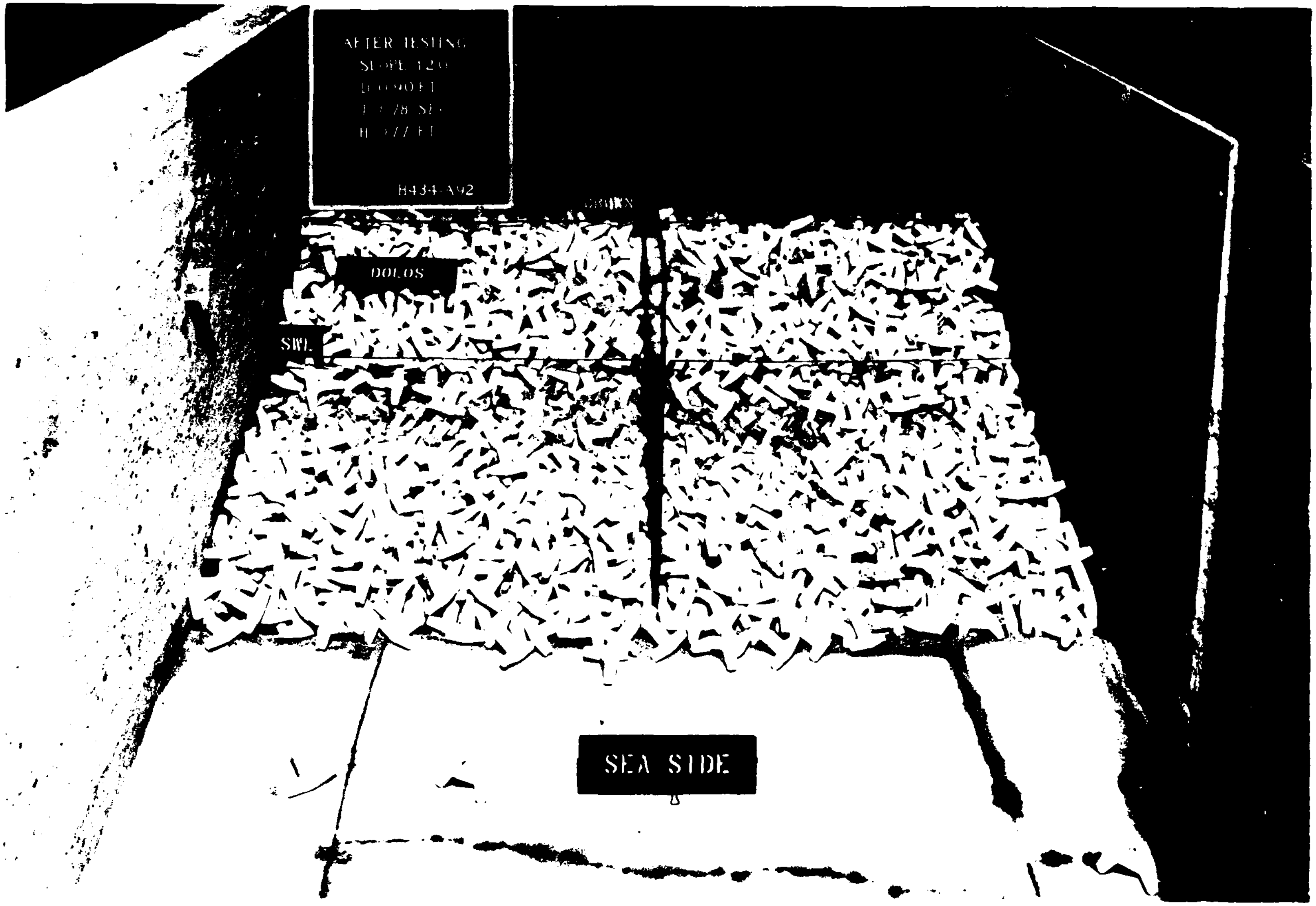


Photo 23. Sea-side view of 2.5-ft dolos sections after completion of test series 3 of the breaking wave tests

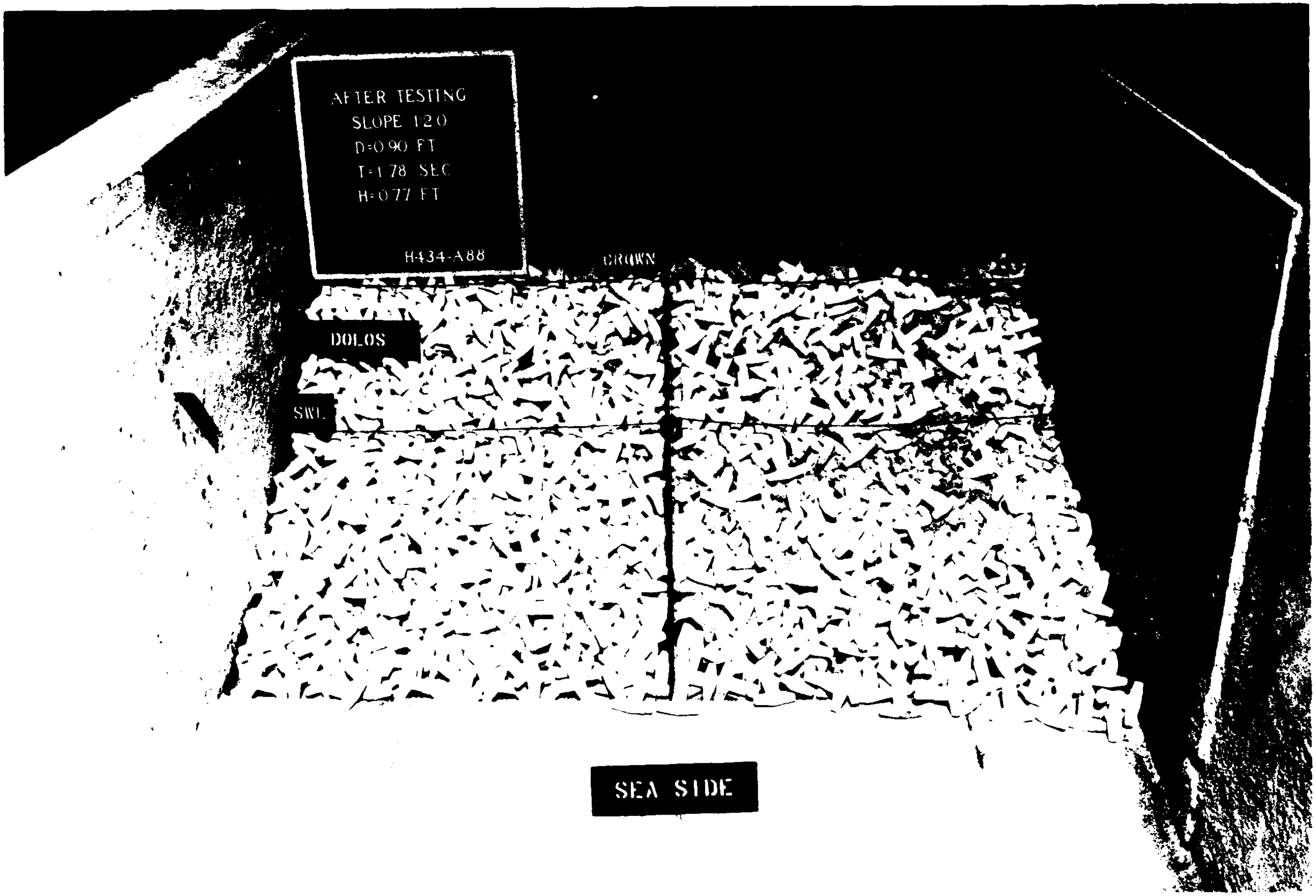


Photo 24. Sea-side view of 2.5-ft dolos sections after completion of test series 4 of the breaking wave tests

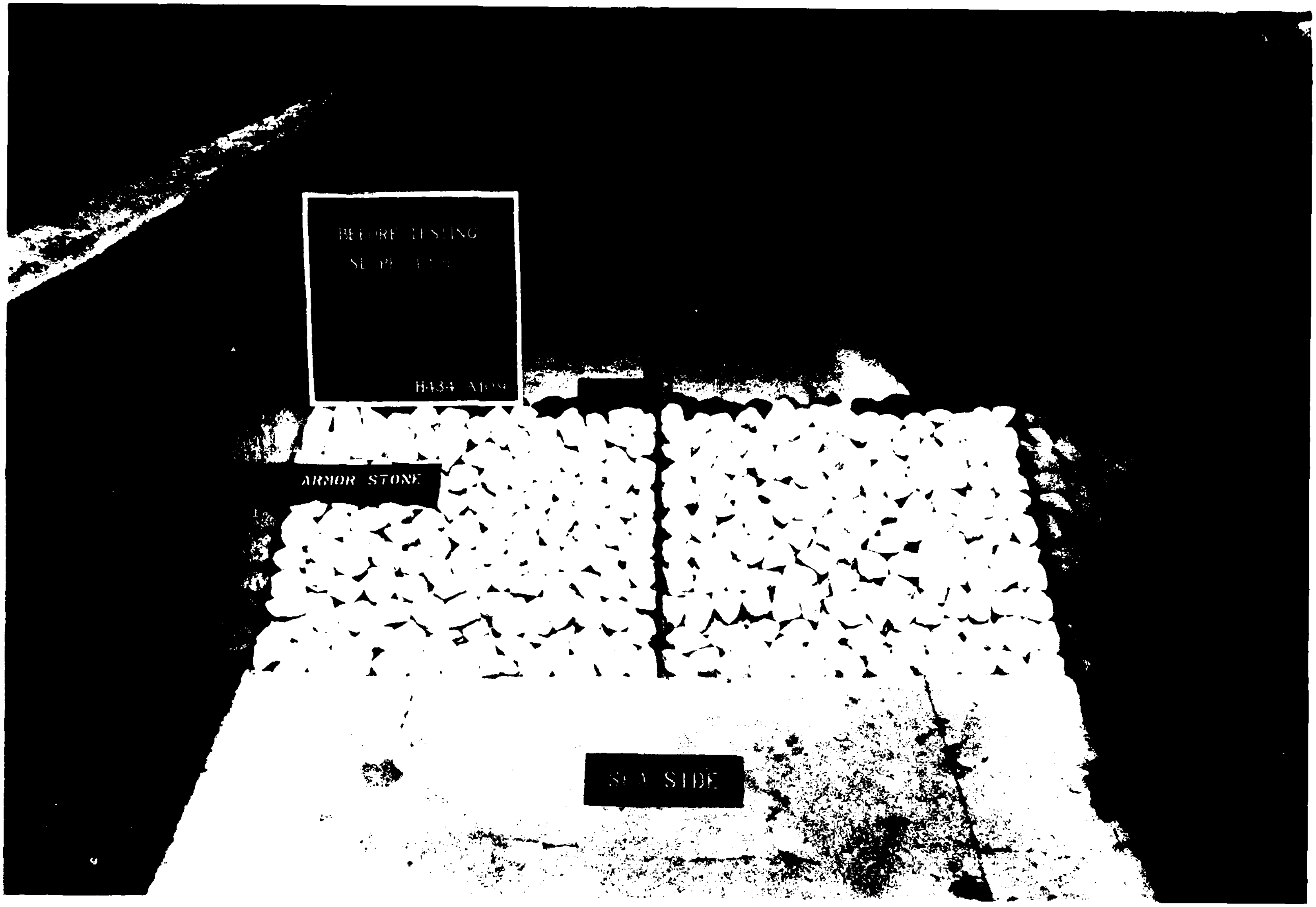


Photo 25. Sea-side view of 2.5-ft stone sections before wave attack at a 1V on 1.5H sea-side structure slope

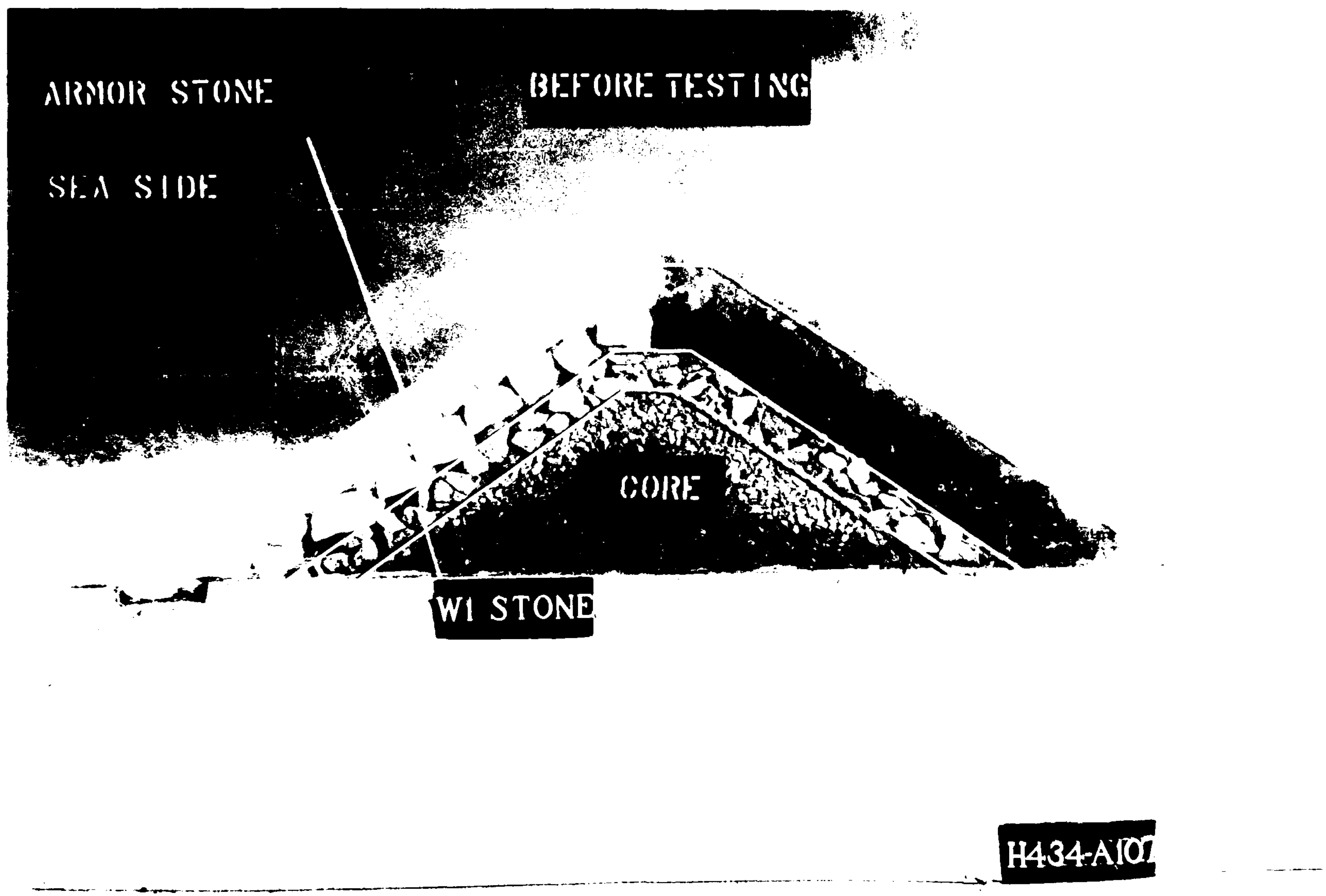


Photo 26. End view of 2.5-ft stone sections before wave attack at a 1V on 1.5H sea-side structure slope

Photo 27. Sea-side view of 2.5-ft stone sections after completion of test series 1 of the breaking wave tests

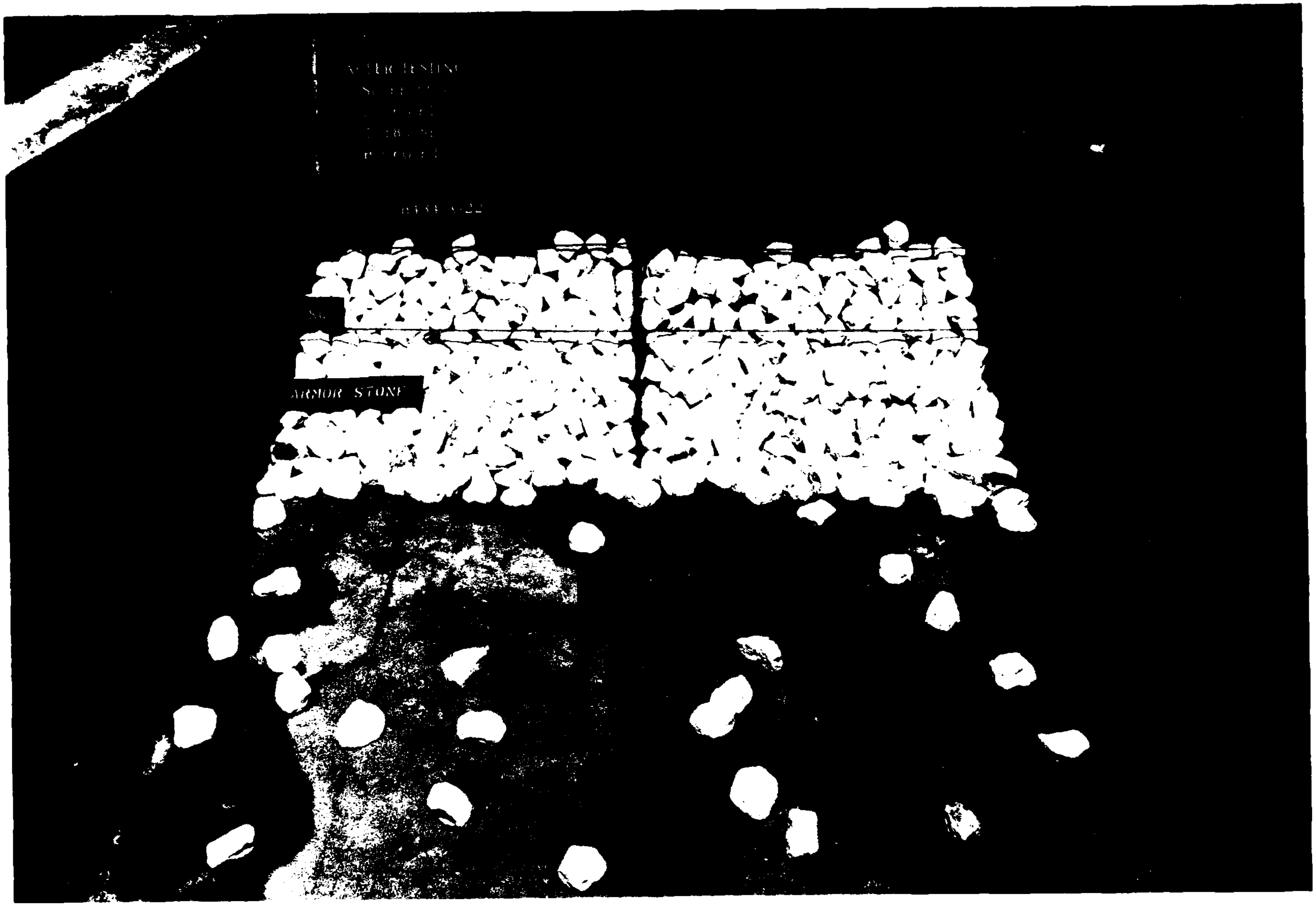


Photo 28. Sea-side view of 2.5-ft stone sections after completion of test series 2 of the breaking wave tests

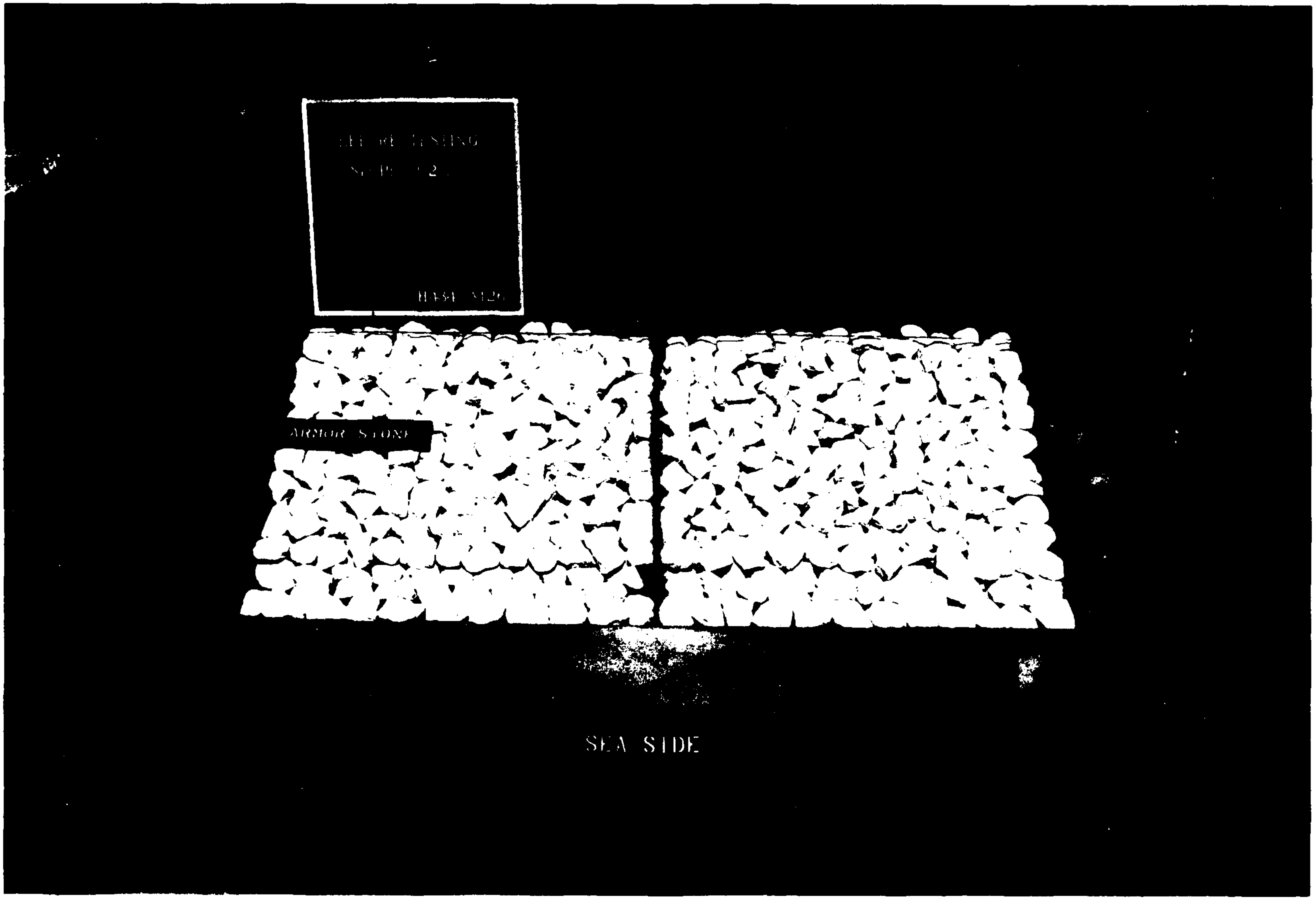


Photo 29. Sea-side view of 2.5-ft stone sections before wave attack at a 1V on 2H sea-side structure slope

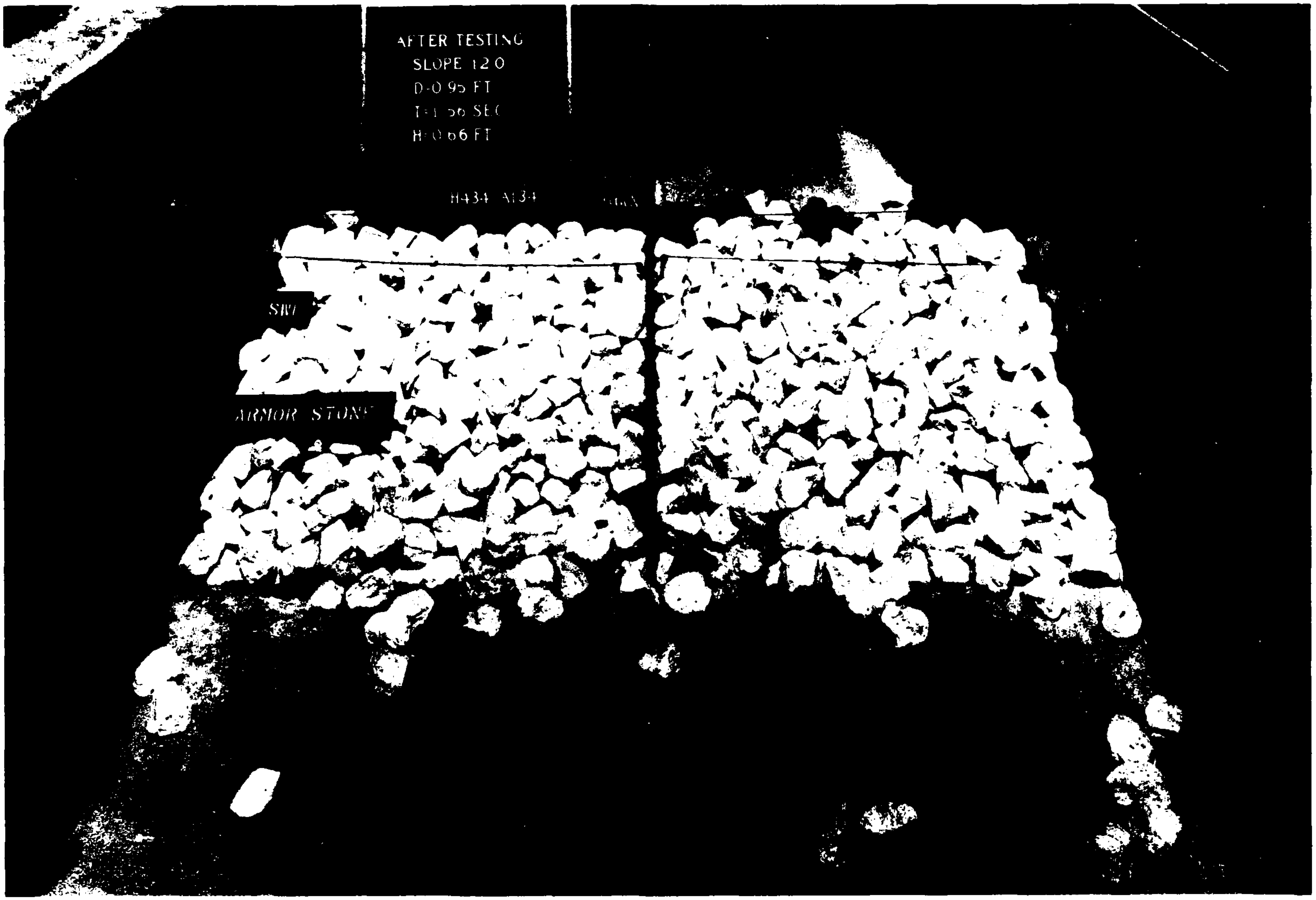


Photo 30. Sea-side view of 2.5-ft stone sections after completion of test series 3 of the breaking wave tests

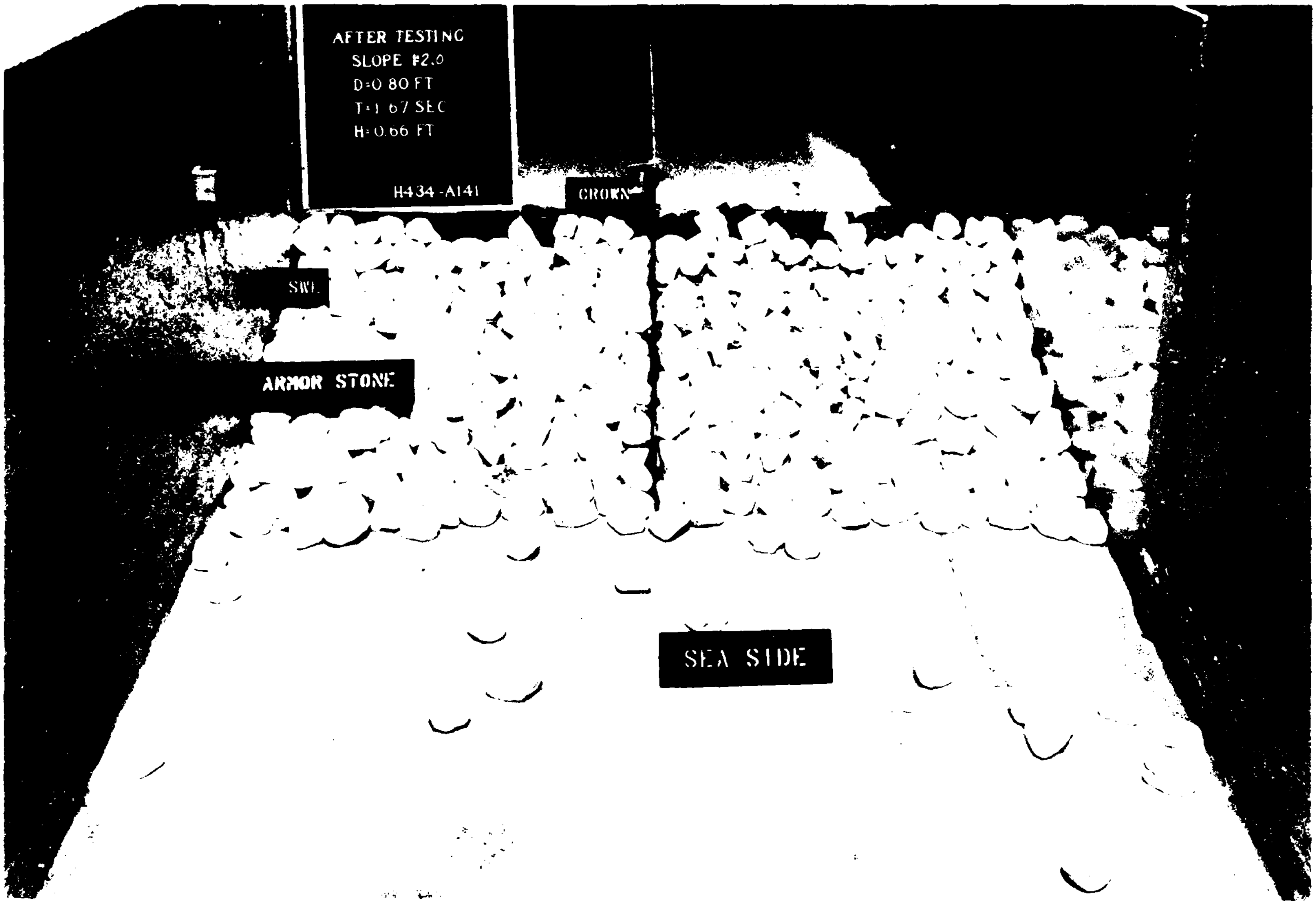
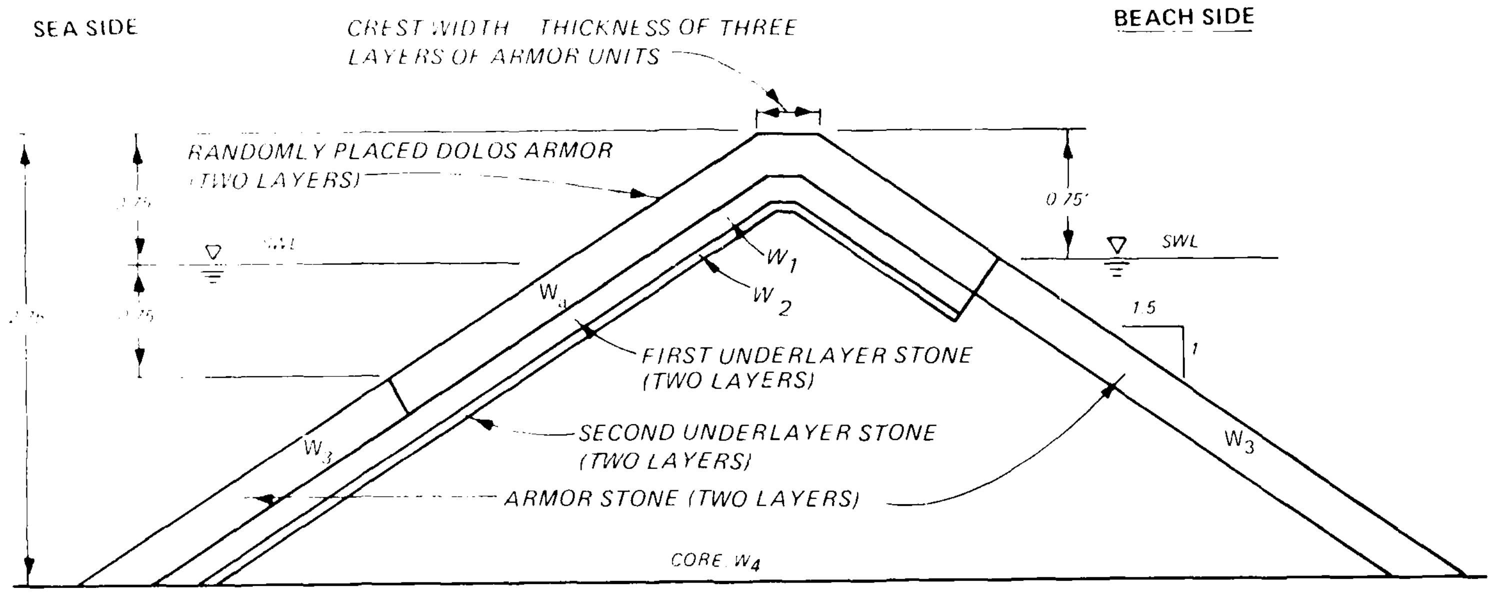


Photo 31. Sea-side view of 2.5-ft stone sections after completion of test series 4 of the breaking wave tests



MATERIAL WEIGHTS

W_a 0.276 - LB DOLOS

W_1 W_a 5

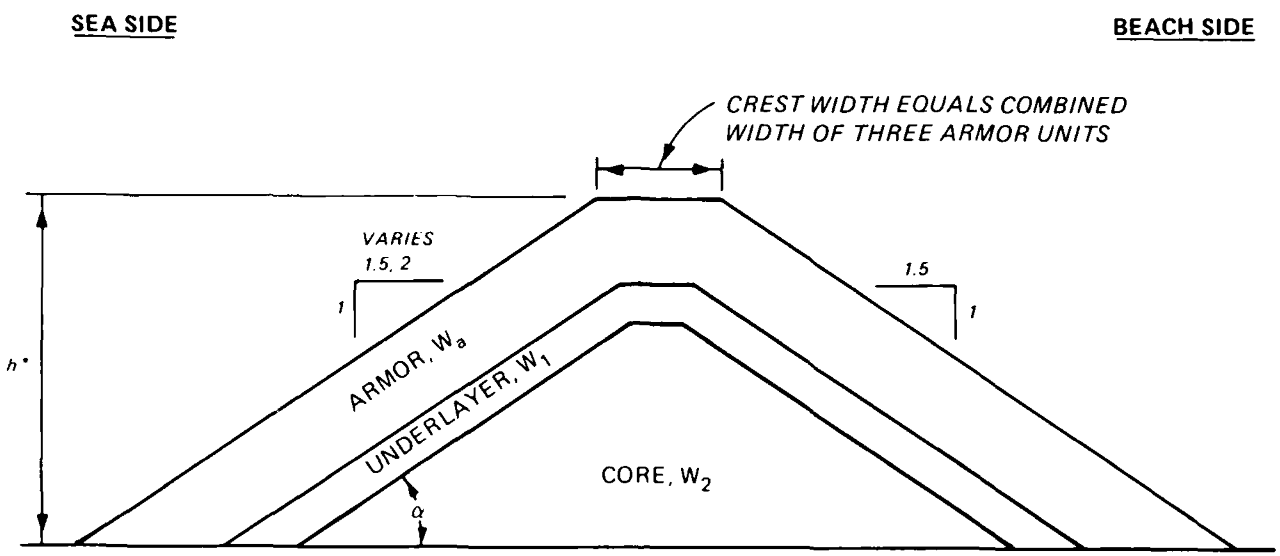
W_2 W_1 20

$W_3 \approx W_a$

W_4 W_a 500 TO W_a 3,000

NONBREAKING WAVE TESTS

TYPICAL BREAKWATER
CROSS SECTION

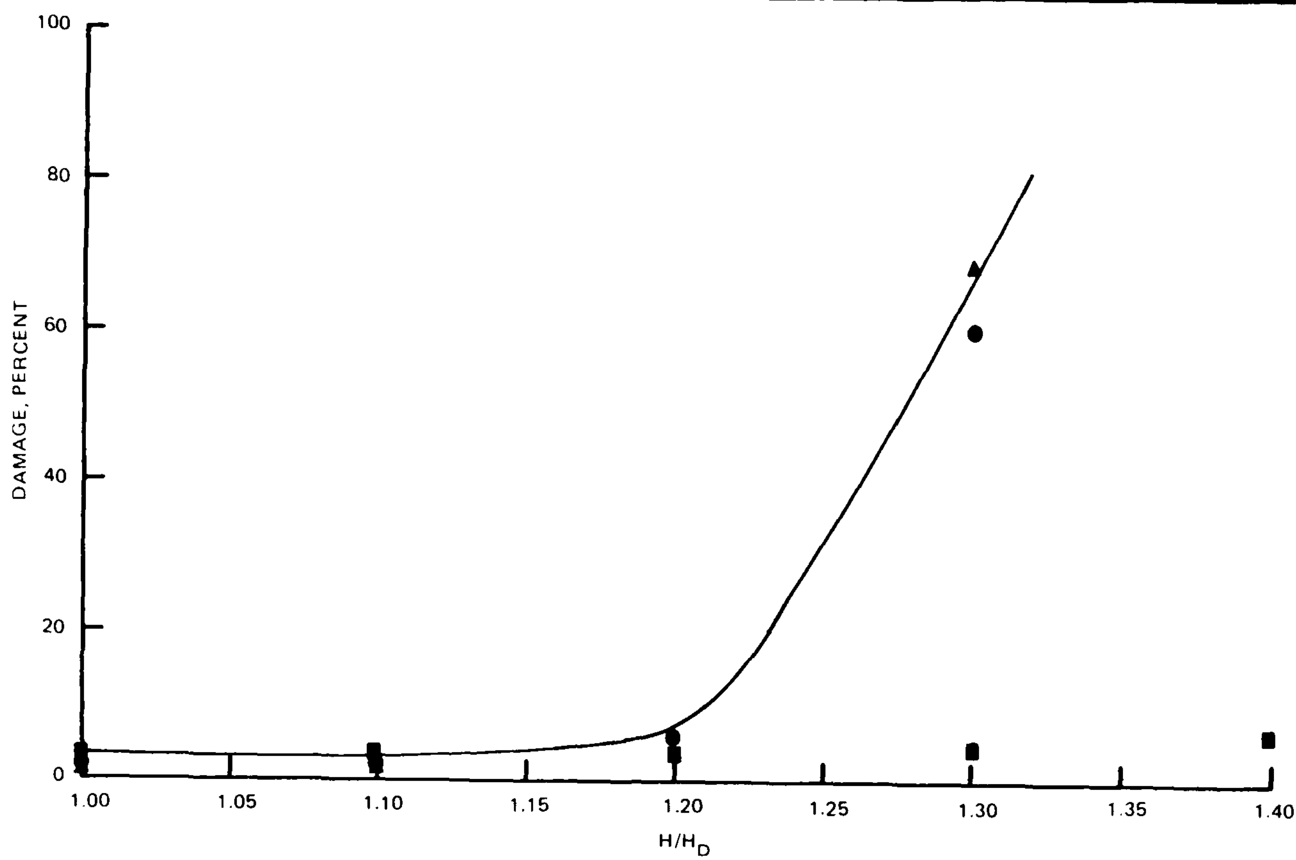


MATERIAL WEIGHTS, LB

W_a	W_1	W_2	ARMOR TYPE
0.55	0.055	0.000138 TO 0.0028	STONE
0.276	0.055	0.000069 TO 0.0014	DOLOS

* TOTAL STRUCTURE HEIGHT (h) VARIED FROM 1.0 FT TO 1.2 FT DEPENDING ON THE COMBINATION OF STRUCTURE SLOPE, ARMOR WEIGHT, AND WATER DEPTH BEING INVESTIGATED.

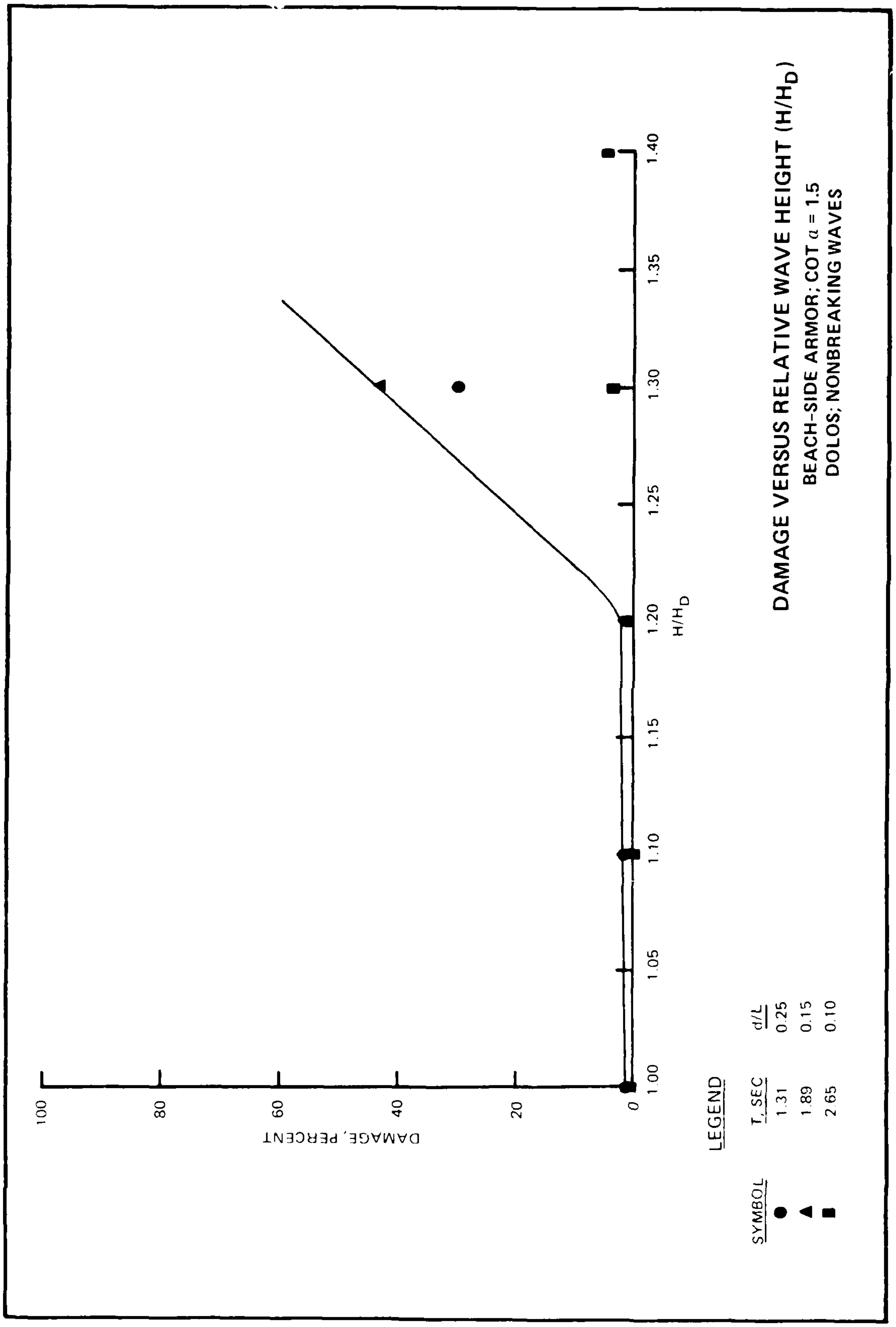
BREAKING WAVE TESTS
TYPICAL BREAKWATER CROSS SECTION



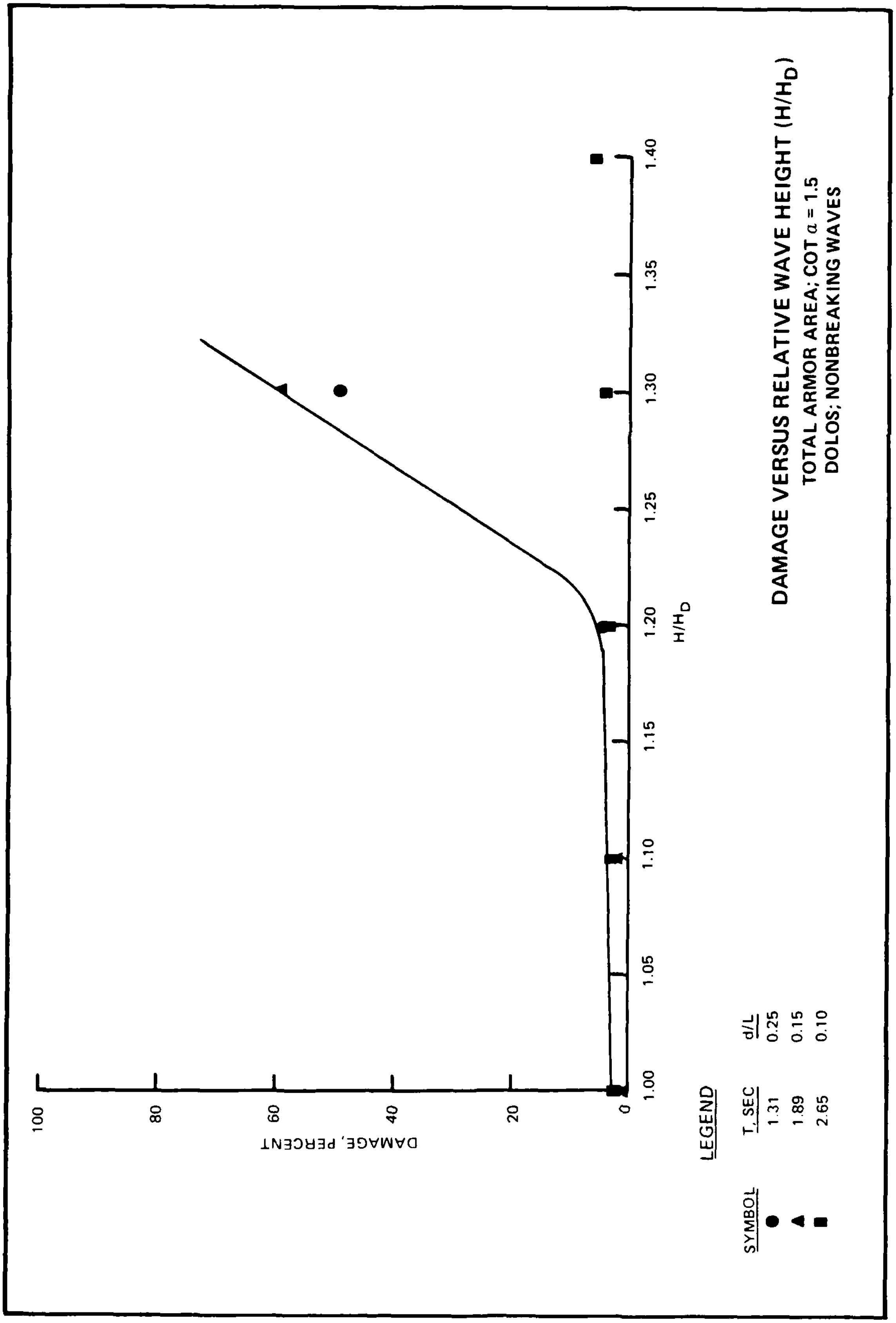
LEGEND

SYMBOL	T, SEC	d/L
●	1.31	0.25
▲	1.89	0.15
■	2.65	0.10

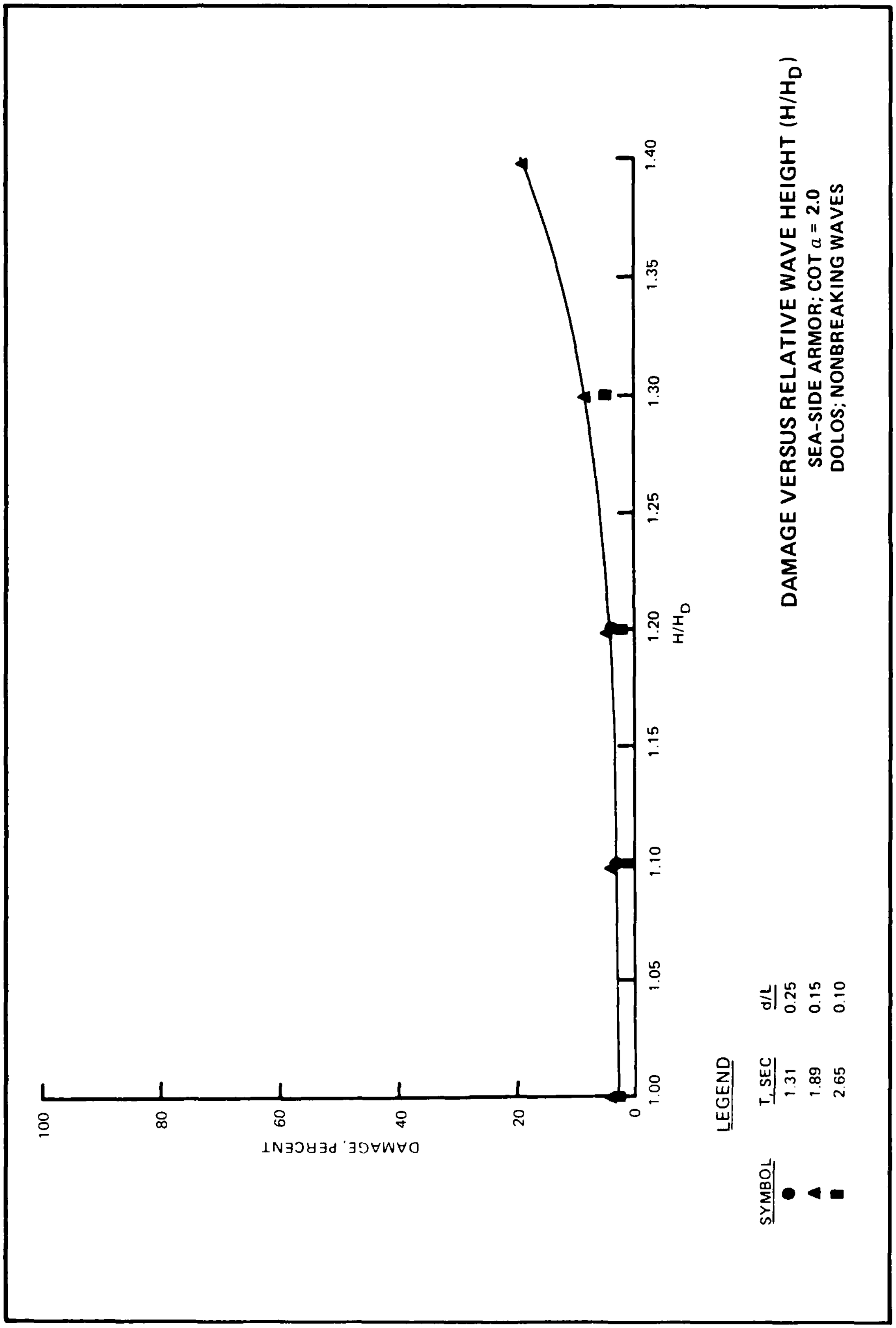
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
SEA-SIDE ARMOR; COT $\alpha = 1.5$
DOLOS; NONBREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
BEACH-SIDE ARMOR; COT α = 1.5
DOLOS; NONBREAKING WAVES

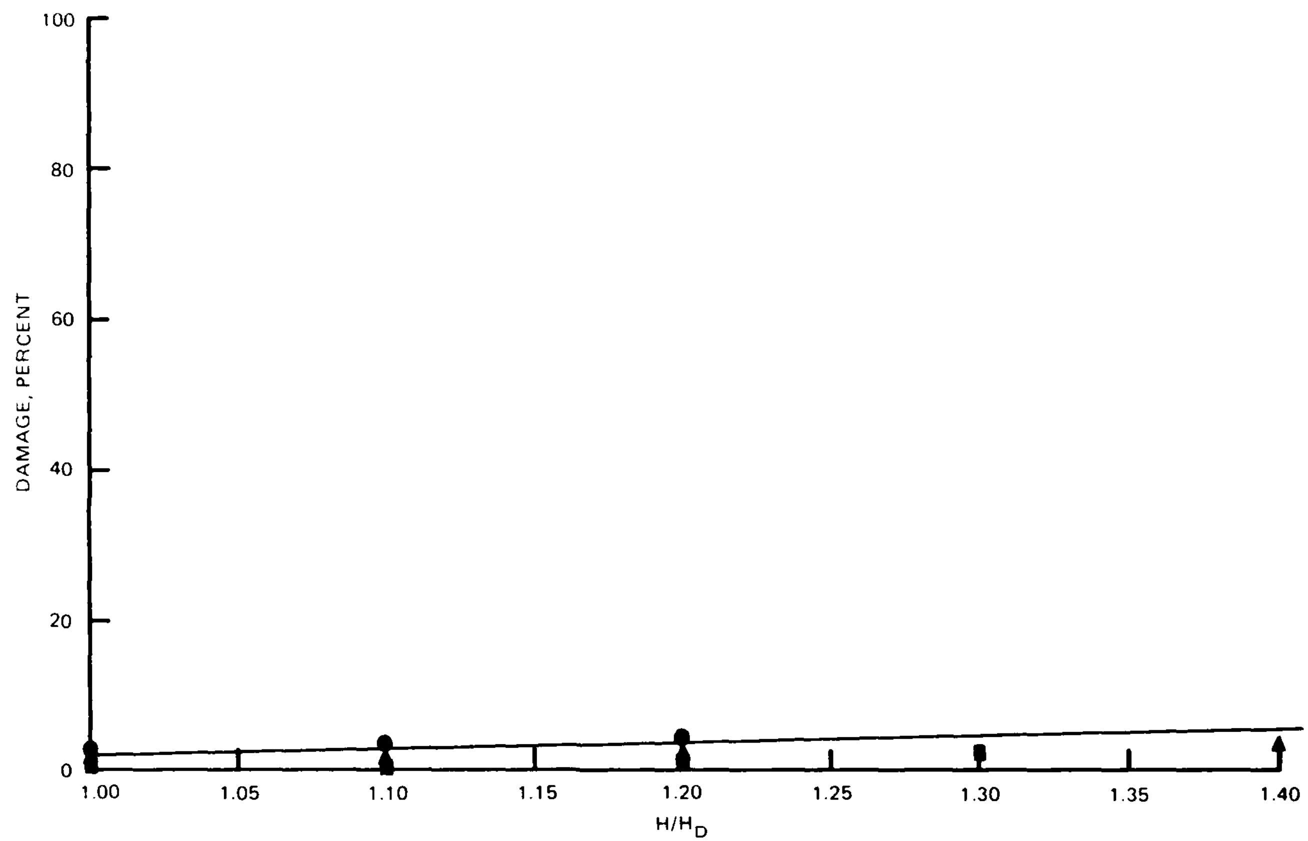


DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
TOTAL ARMOR AREA; COT α = 1.5
DOLOS; NONBREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
SEA-SIDE ARMOR; COT α = 2.0
DOLOS; NONBREAKING WAVES

PLATE 6



LEGEND

SYMBOL	T, SEC	d/L
●	1.31	0.25
▲	1.89	0.15
■	2.65	0.10

DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
BEACH-SIDE ARMOR; COT α = 2.0
DOLOS; NONBREAKING WAVES

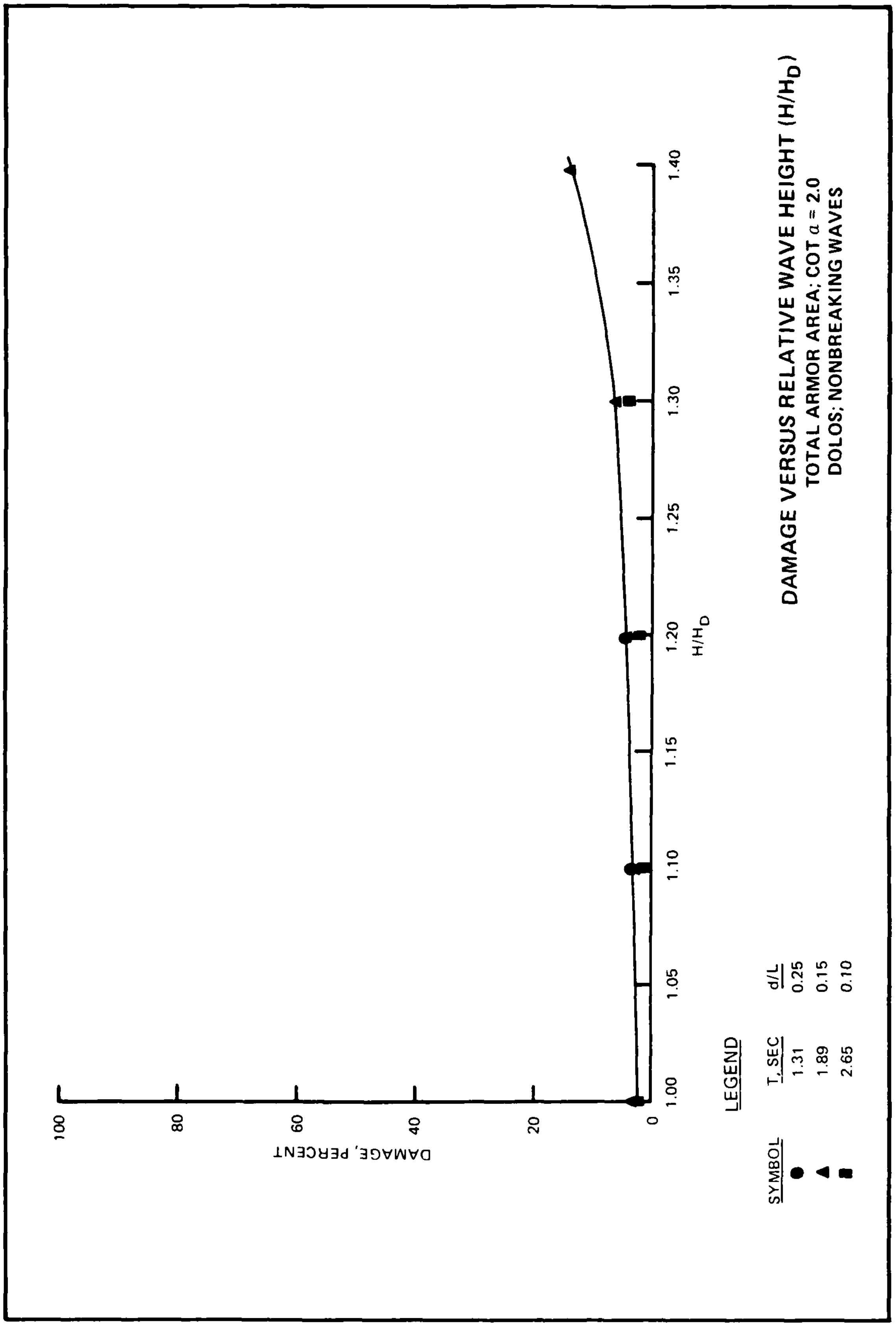
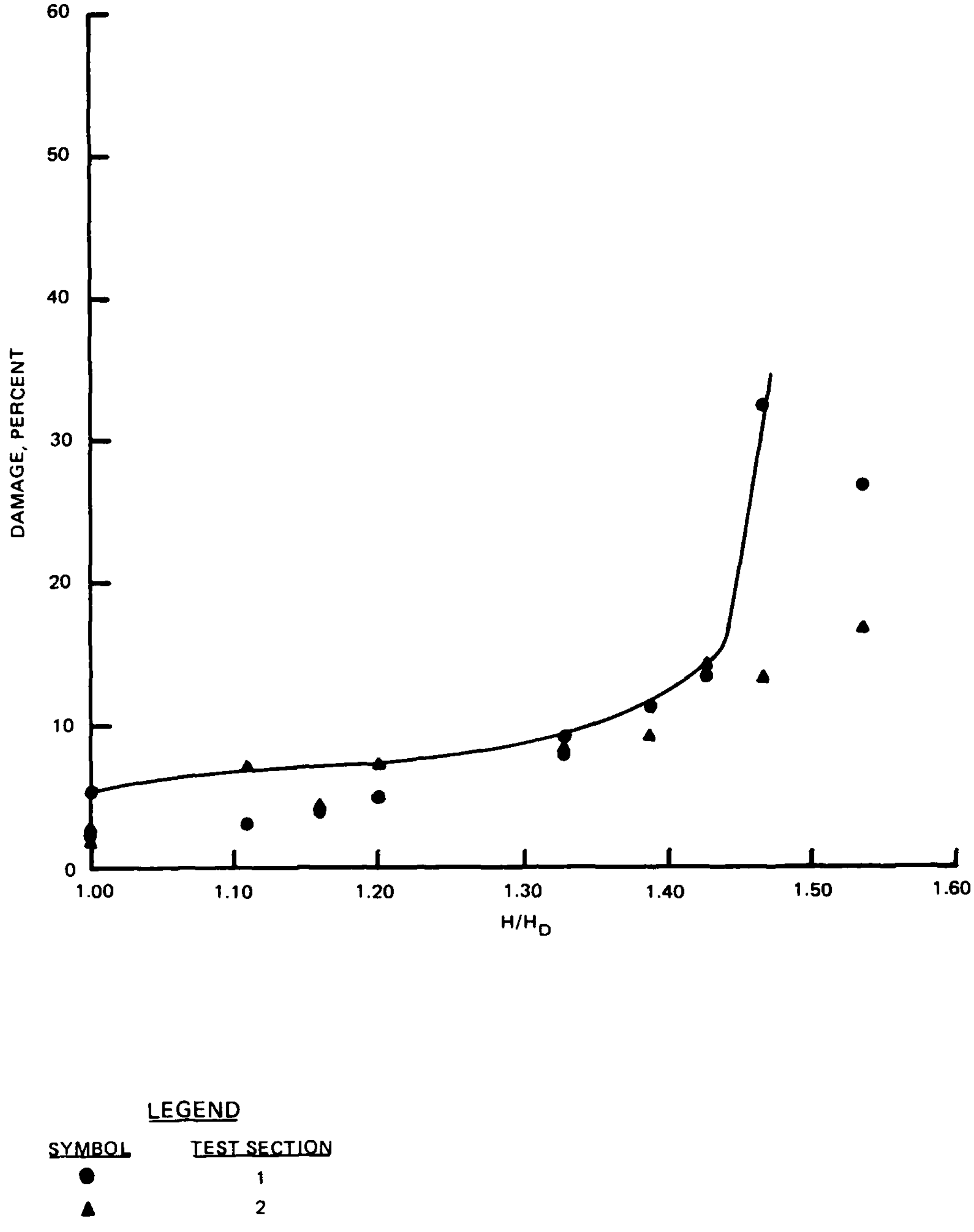
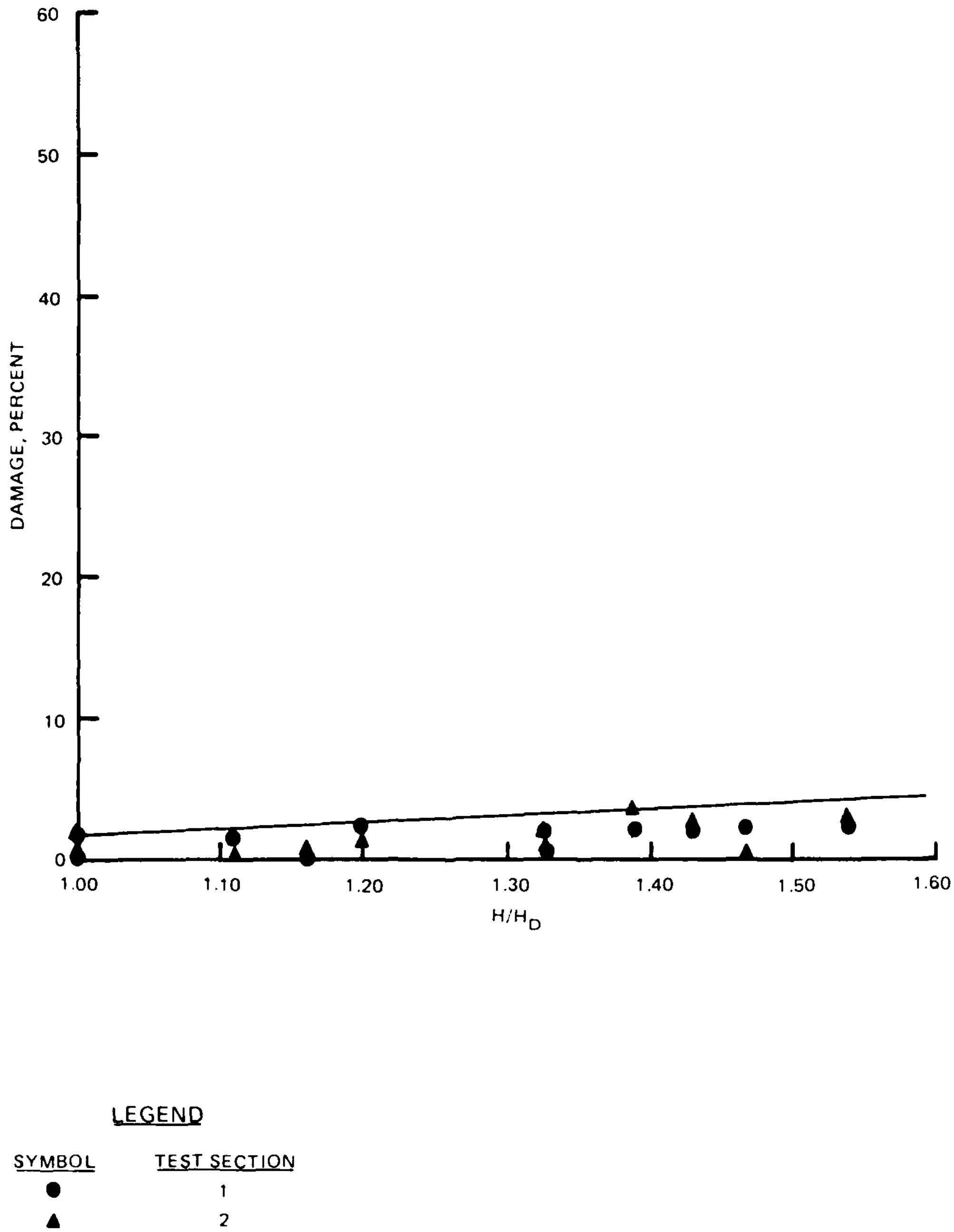

DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H$_D$)
TOTAL ARMOR AREA; COT α = 2.0
DOLOS; NONBREAKING WAVES
DAMAGE, PERCENT
0
20
40
60
80
100
H/H$_D$
1.00
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
LEGEND
SYMBOL
T, SEC
d/L
1.31
0.25
1.89
0.15
2.65
0.10

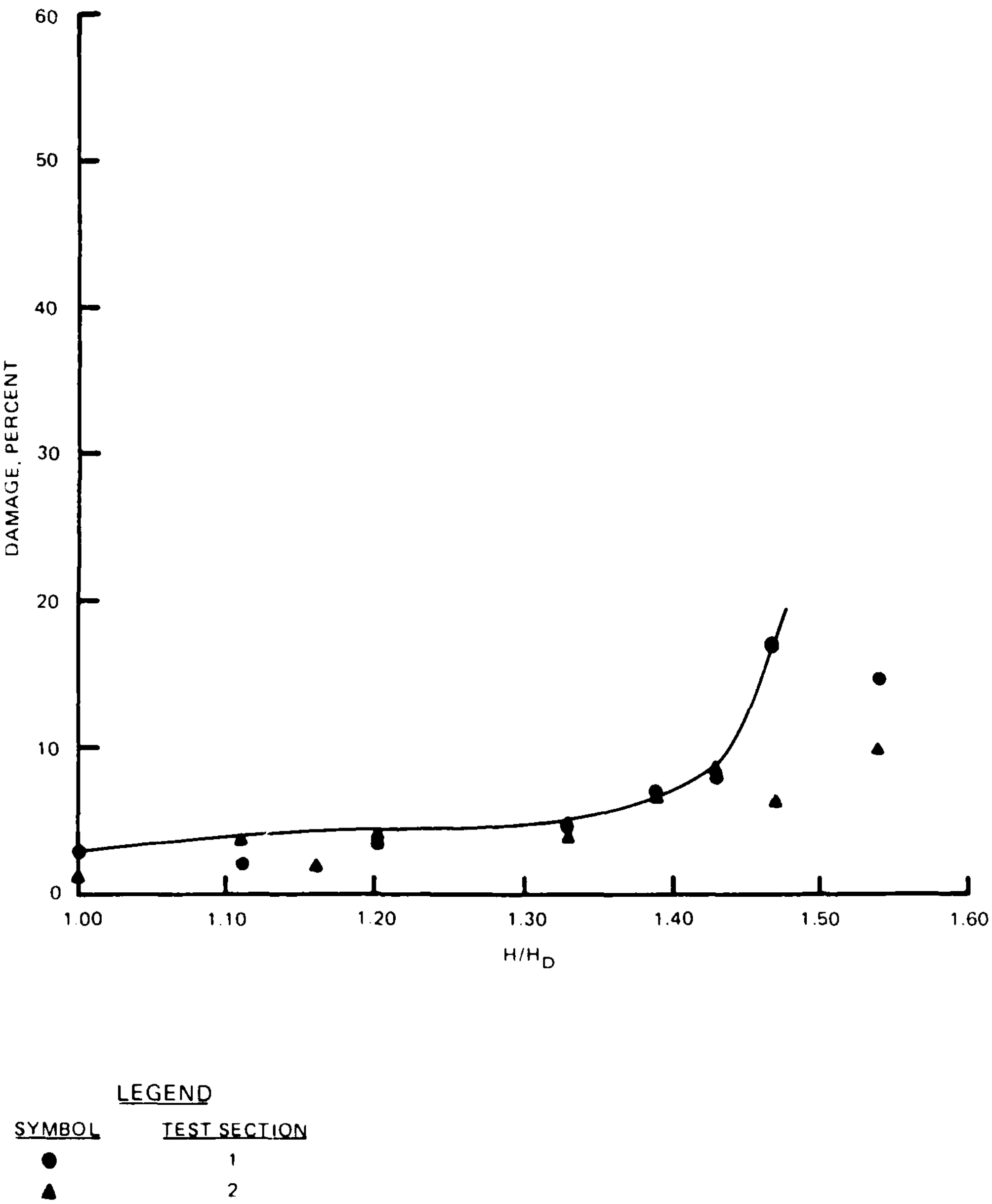
PLATE 8



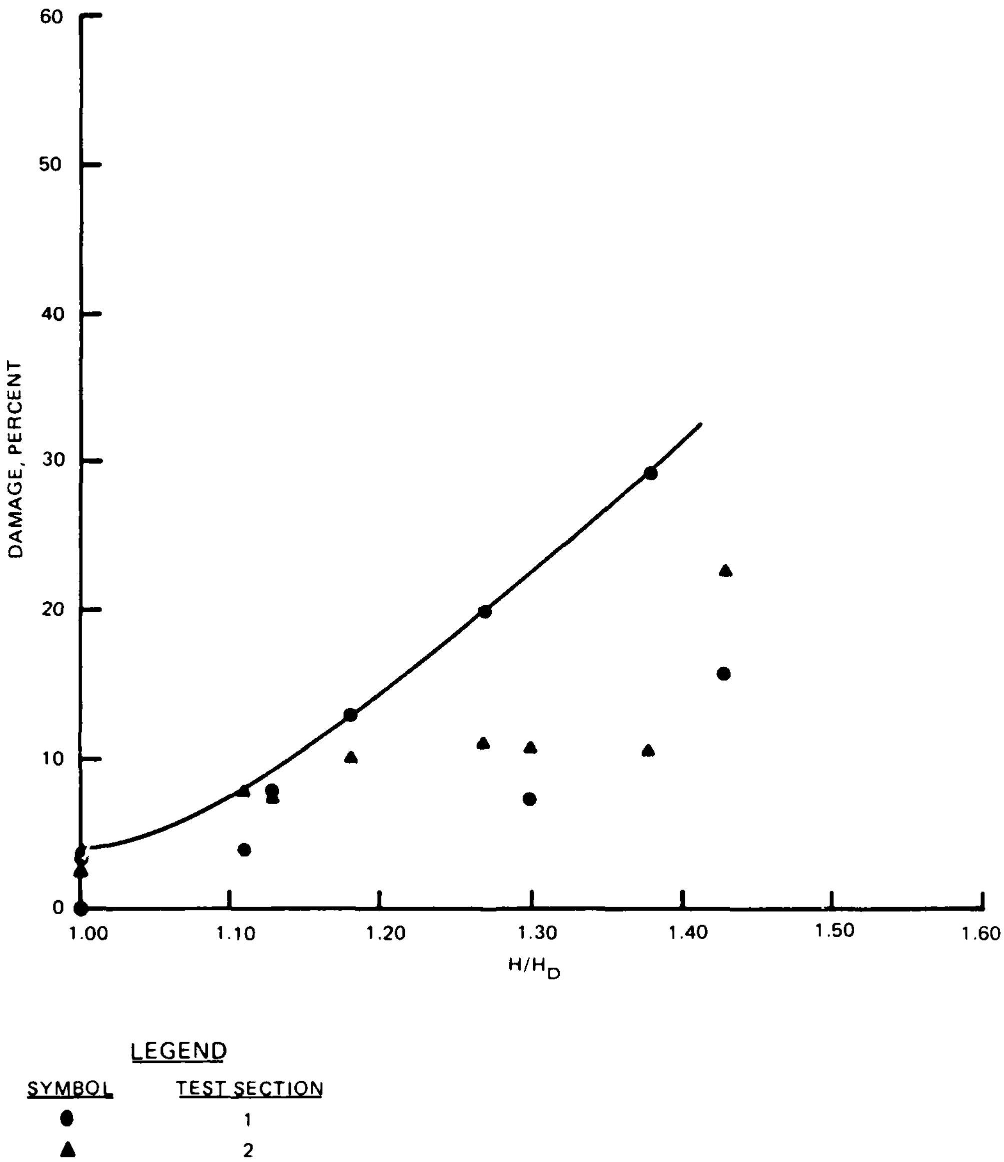
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
SEA-SIDE ARMOR: COT α = 1.5
DOLOS: BREAKING WAVES



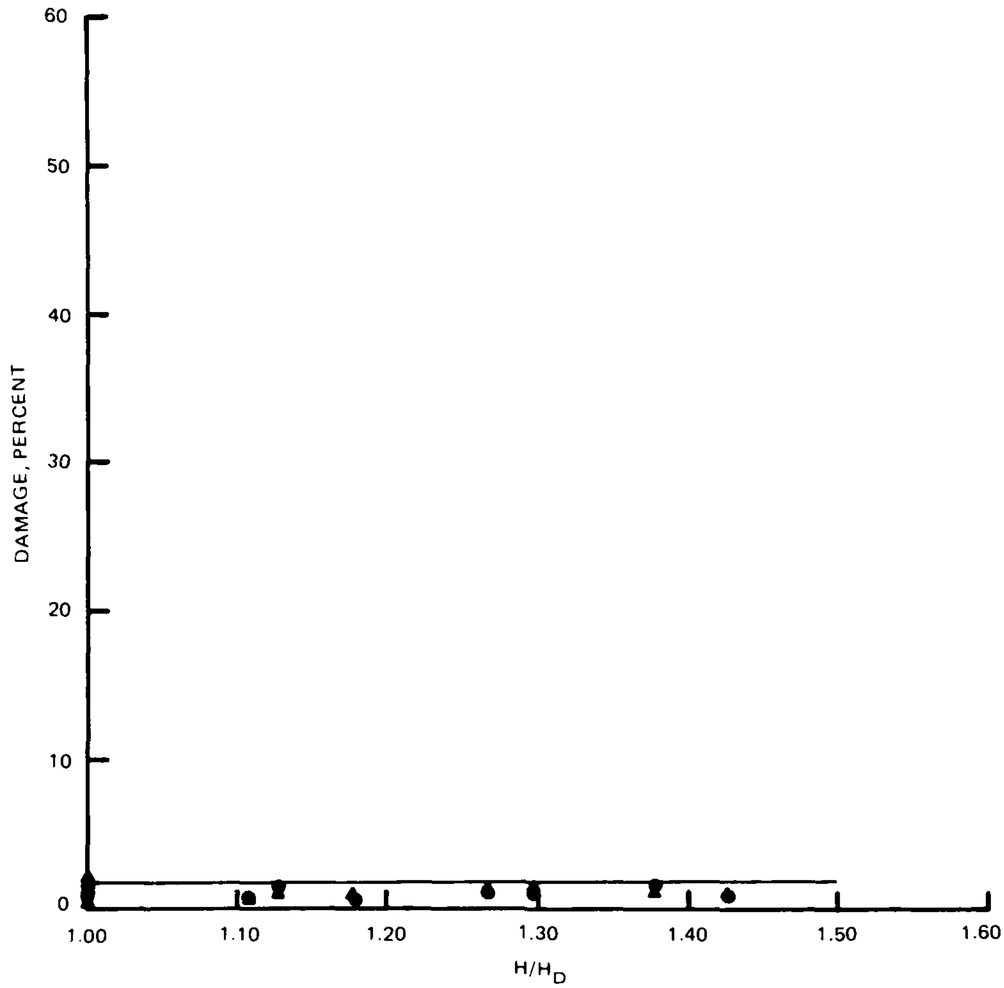
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
BEACH-SIDE ARMOR; COT α = 1.5
DOLOS; BREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
TOTAL ARMOR AREA; COT α = 1.5
DOLOS; BREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
SEA-SIDE ARMOR; COT α = 2.0
DOLOS; BREAKING WAVES



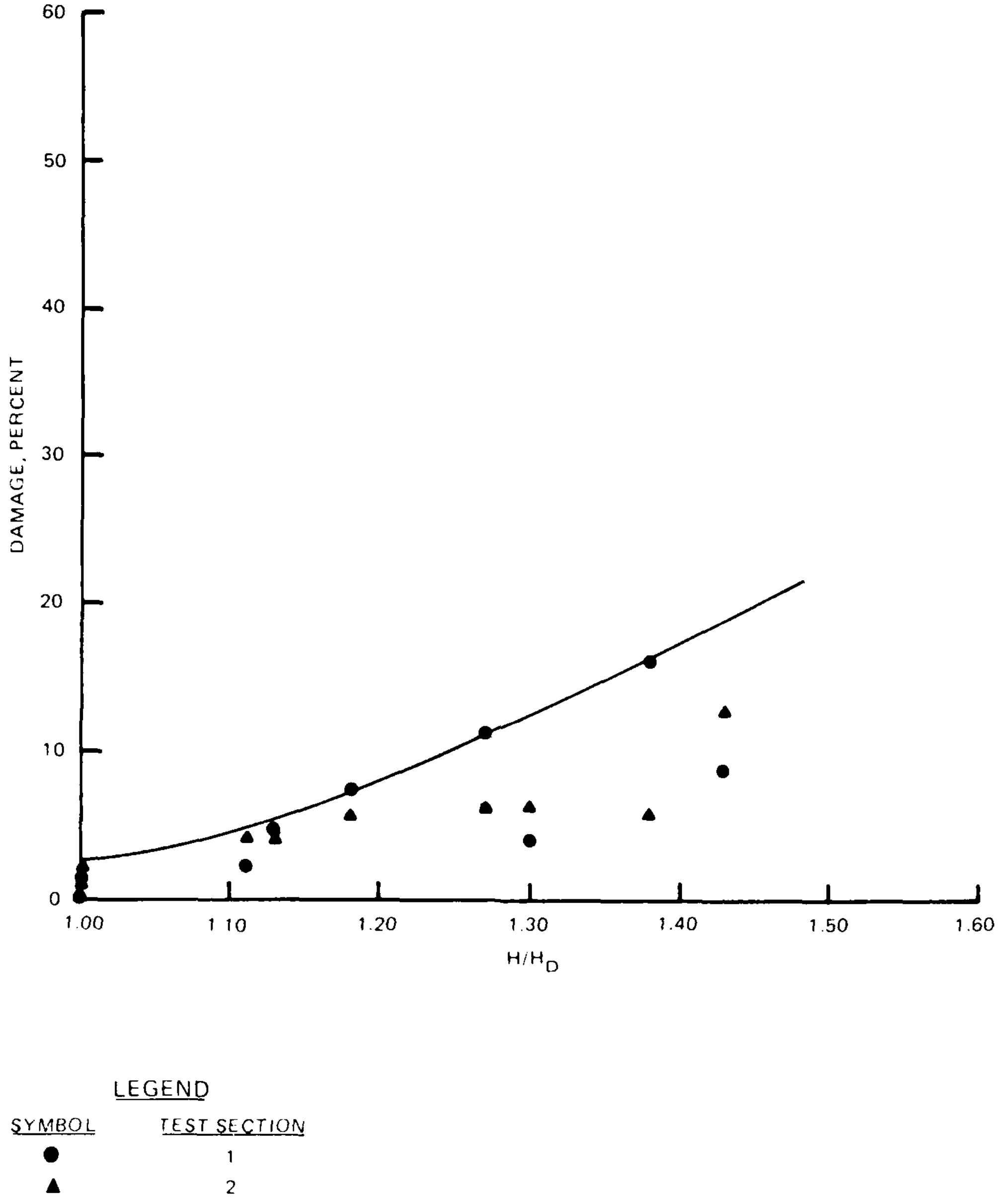
LEGEND

SYMBOL	TEST SECTION
●	1
▲	2

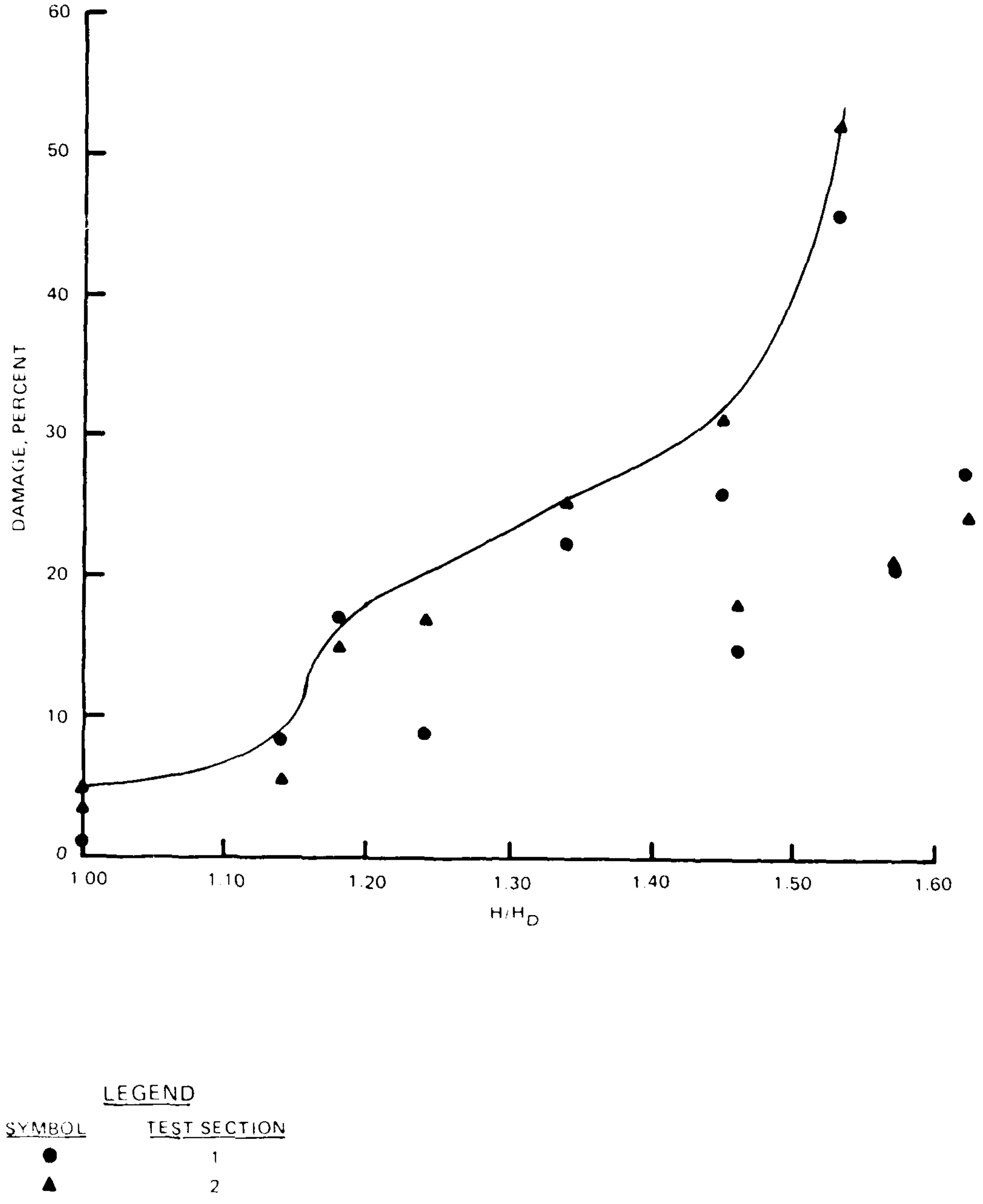
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)

BEACH-SIDE ARMOR; COT α = 2.0

DOLOS; BREAKING WAVES



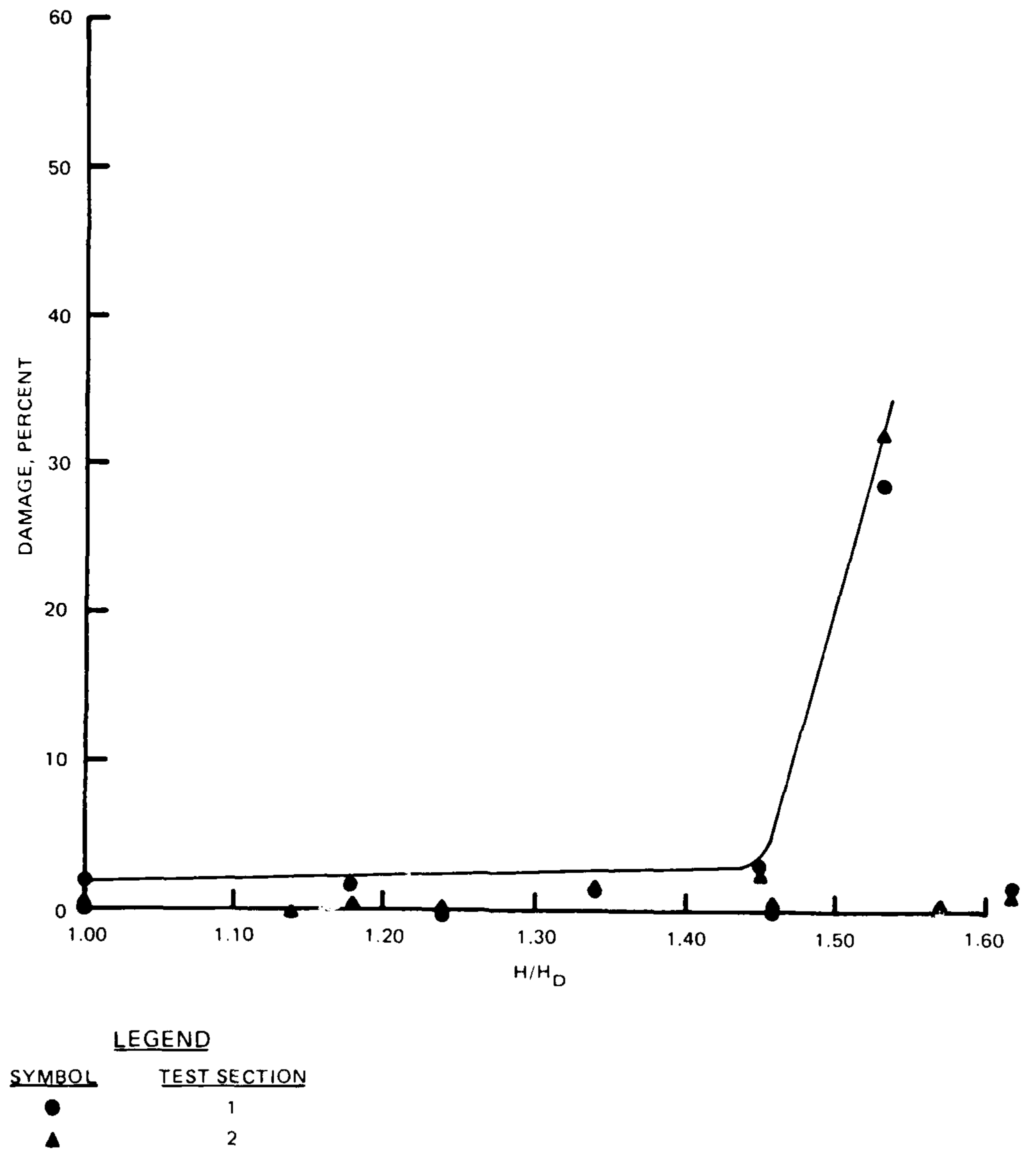
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
TOTAL ARMOR AREA; COT α = 2.0
DOLOS; BREAKING WAVES



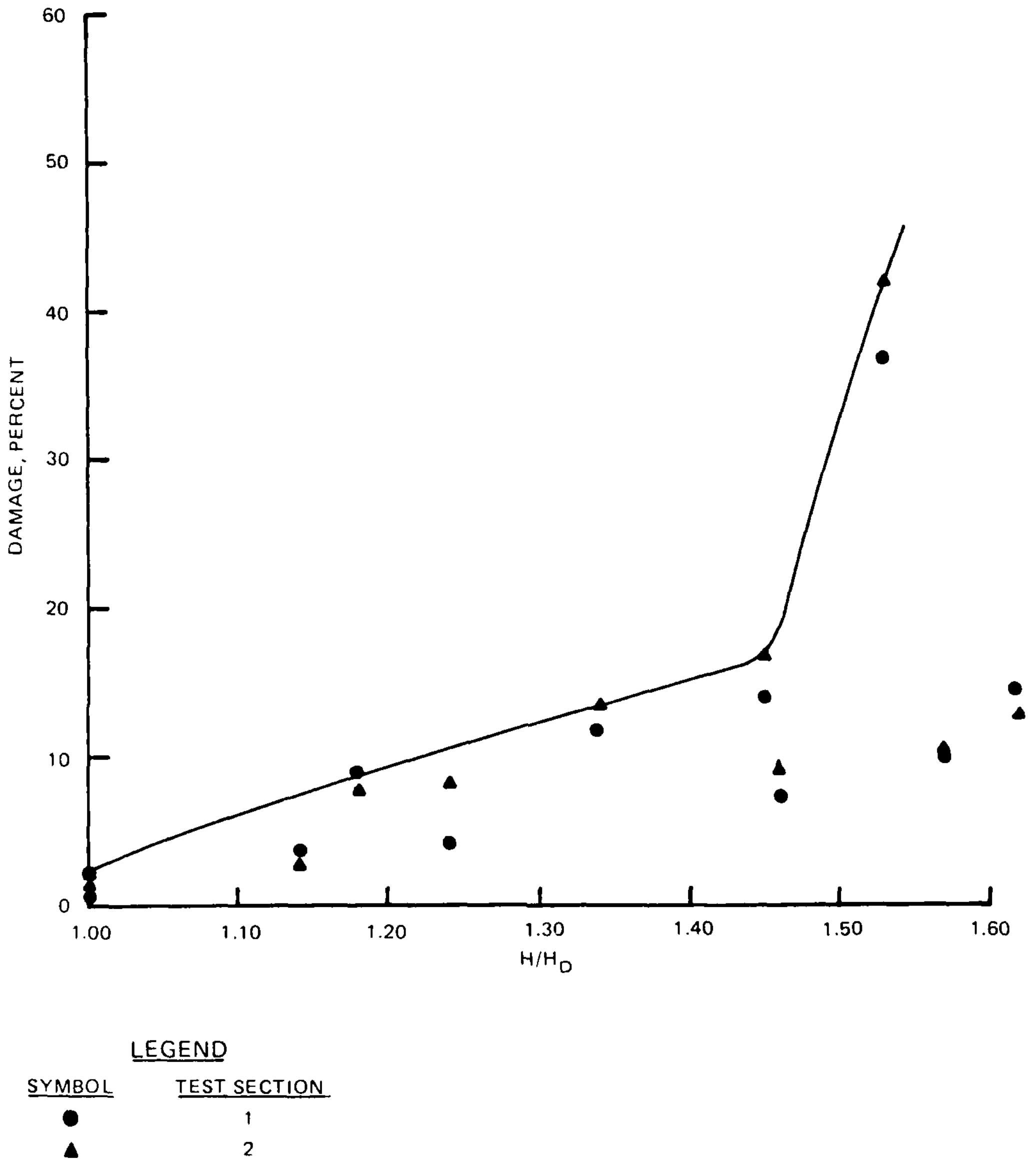
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)

SEA-SIDE ARMOR: COT α = 1.5

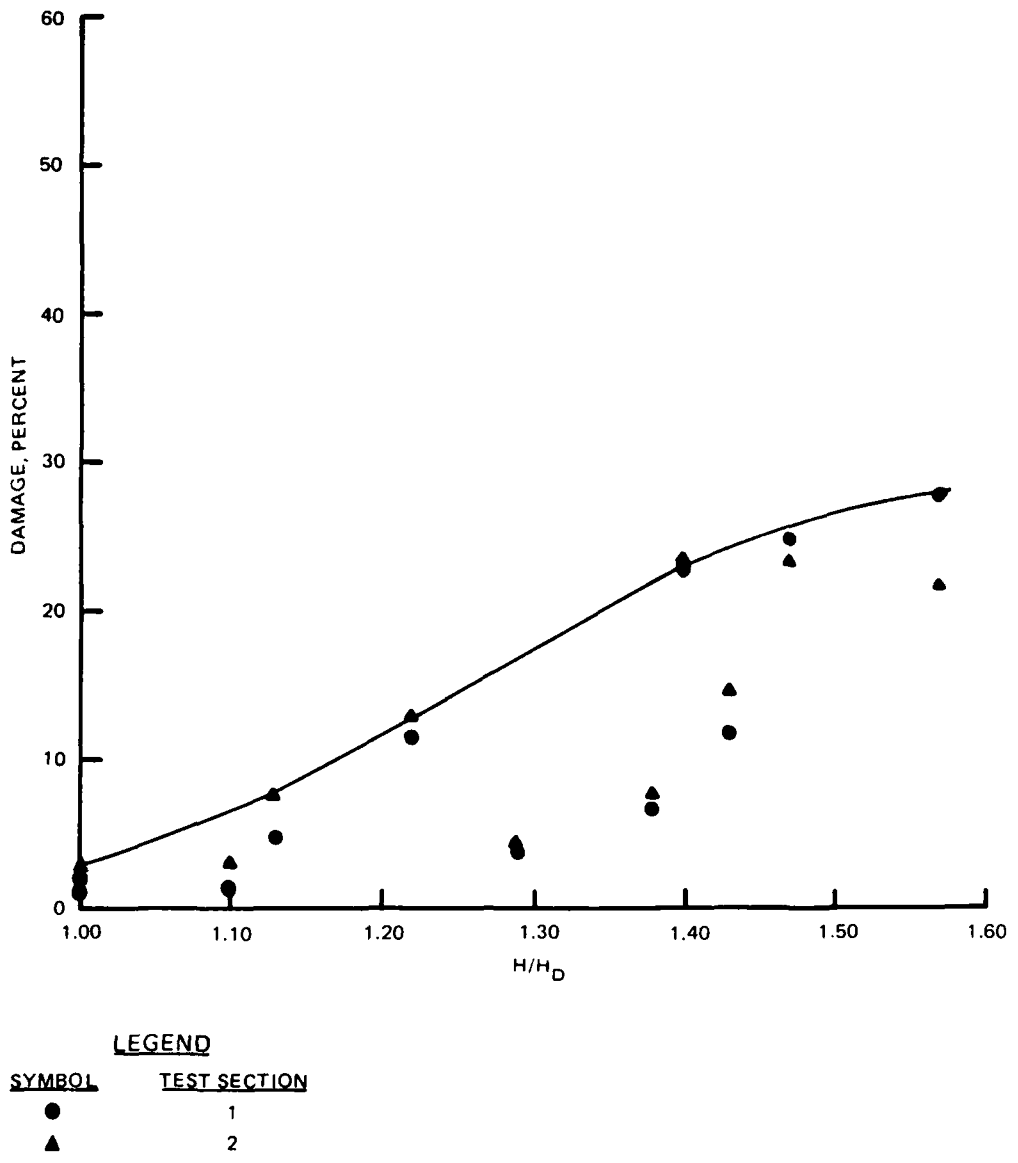
STONE: BREAKING WAVES



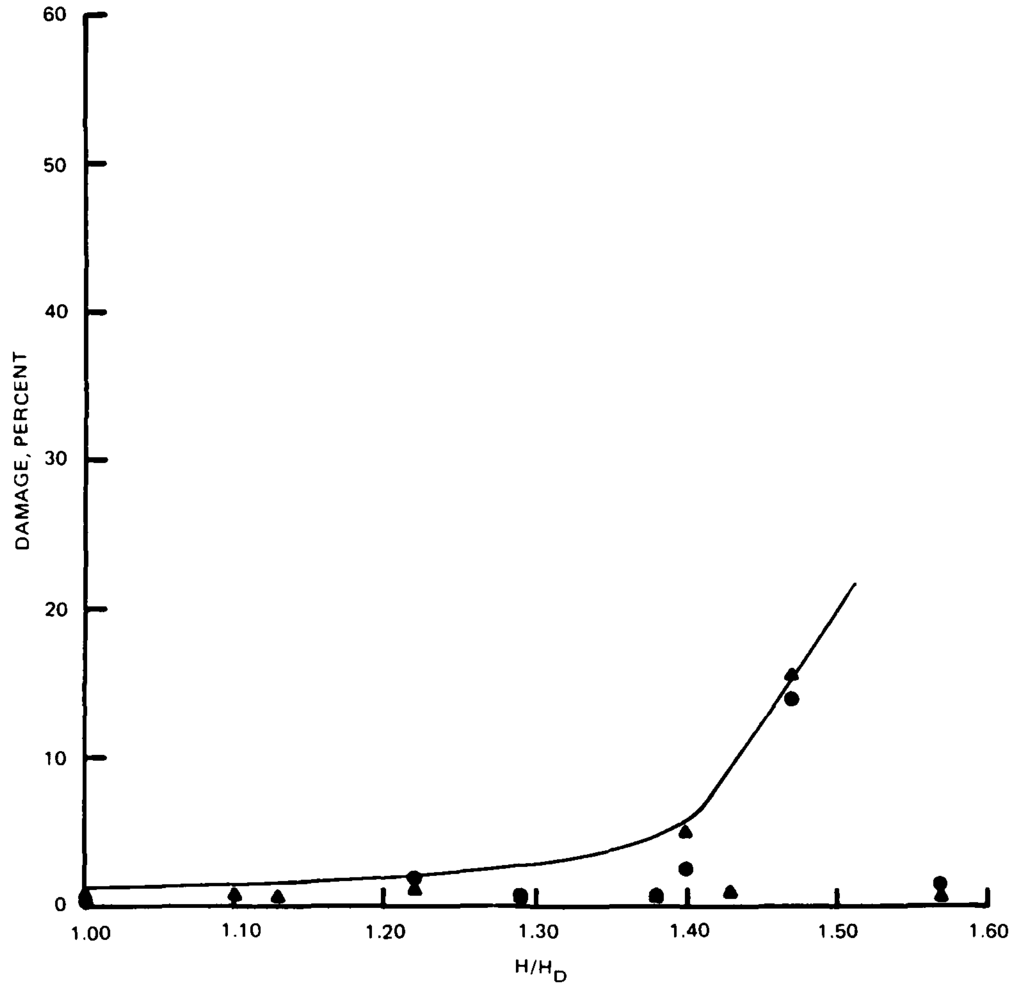
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
BEACH-SIDE ARMOR; COT α = 1.5
STONE; BREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
TOTAL ARMOR AREA; COT a = 1.5
STONE; BREAKING WAVES



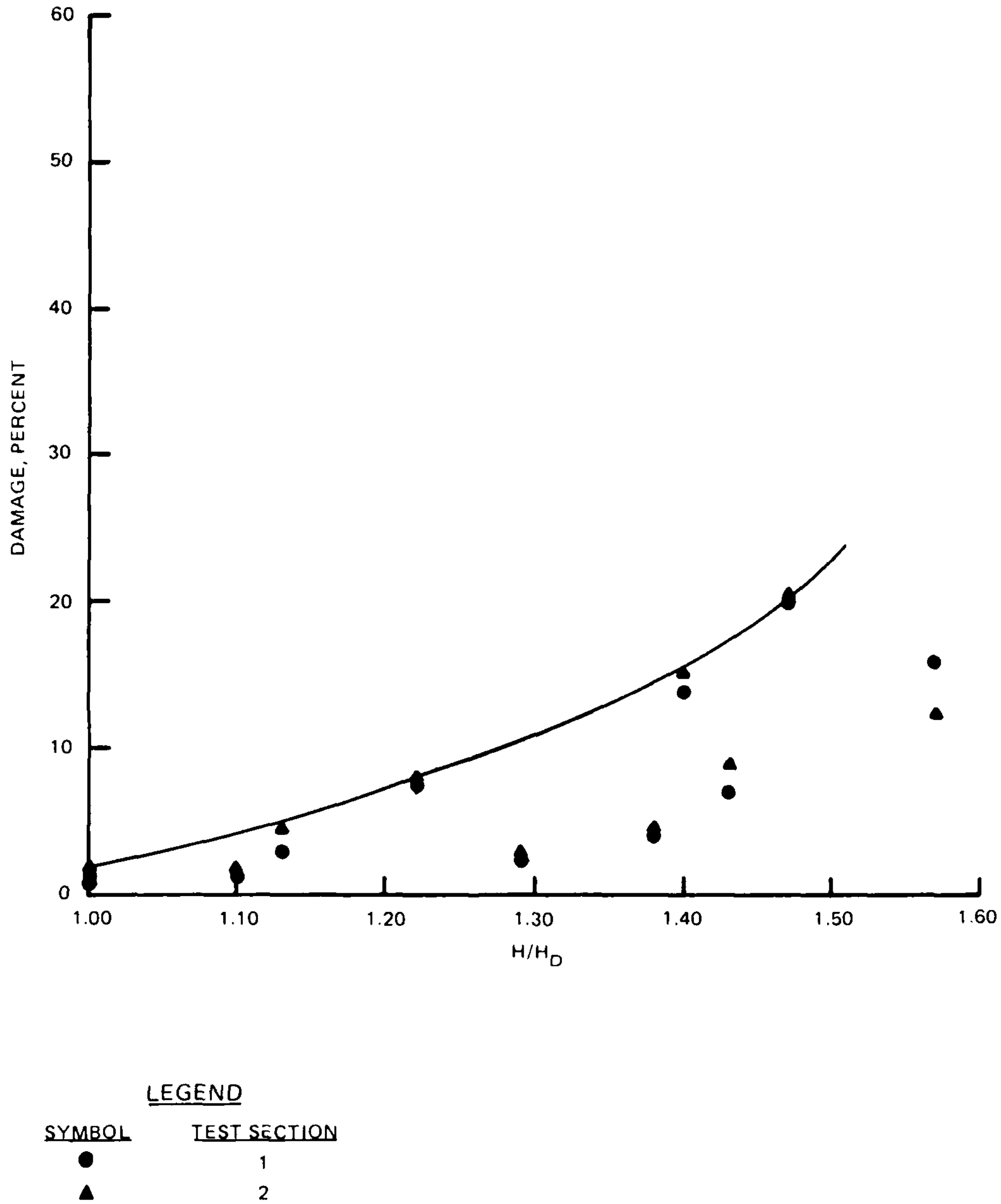
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
SEA-SIDE ARMOR; COT α = 2.0
STONE; BREAKING WAVES



LEGEND

SYMBOL	TEST SECTION
●	1
▲	2

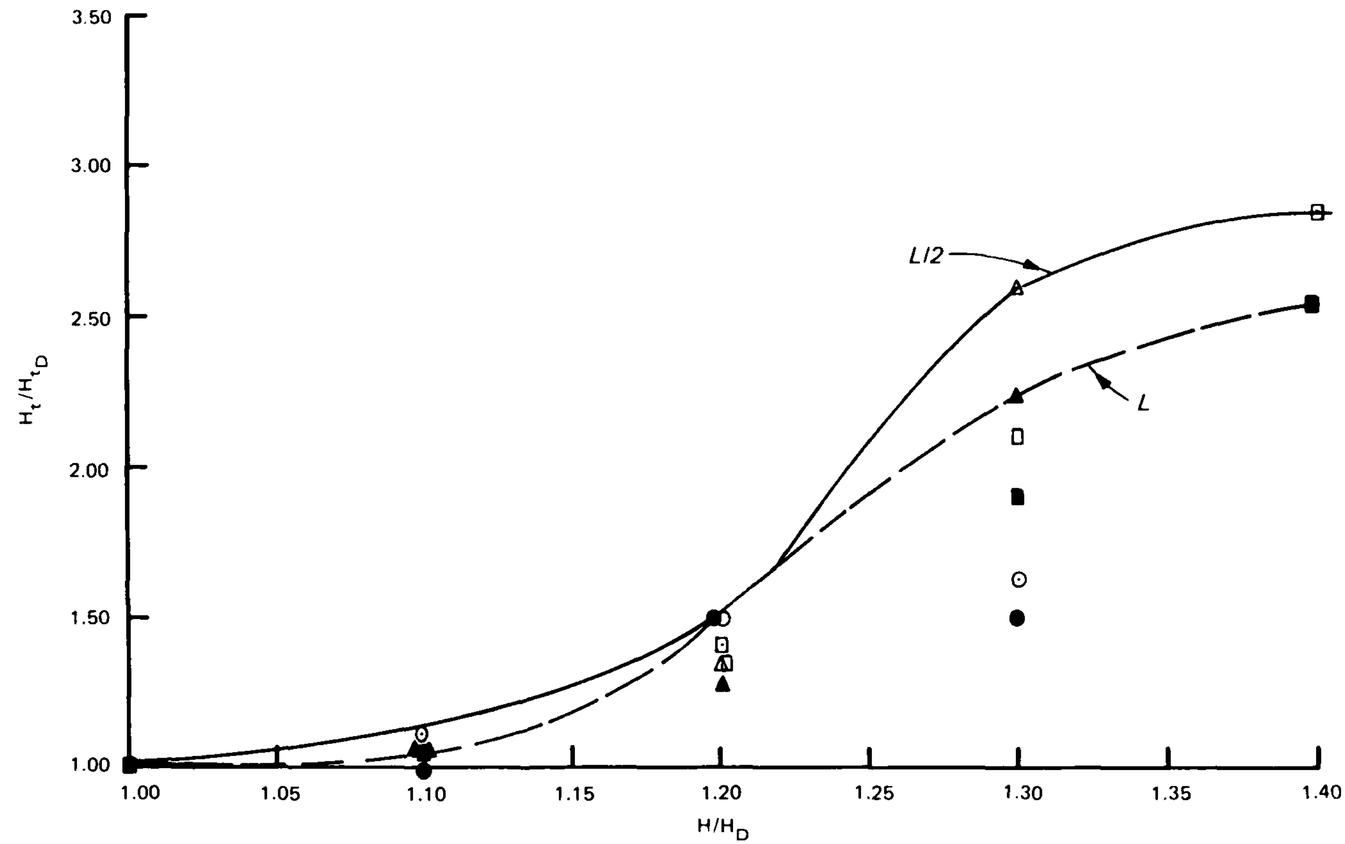
DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)
BEACH-SIDE ARMOR; COT α = 2.0
STONE; BREAKING WAVES



DAMAGE VERSUS RELATIVE WAVE HEIGHT (H/H_D)

TOTAL ARMOR AREA: COT α = 2.0

STONE: BREAKING WAVES

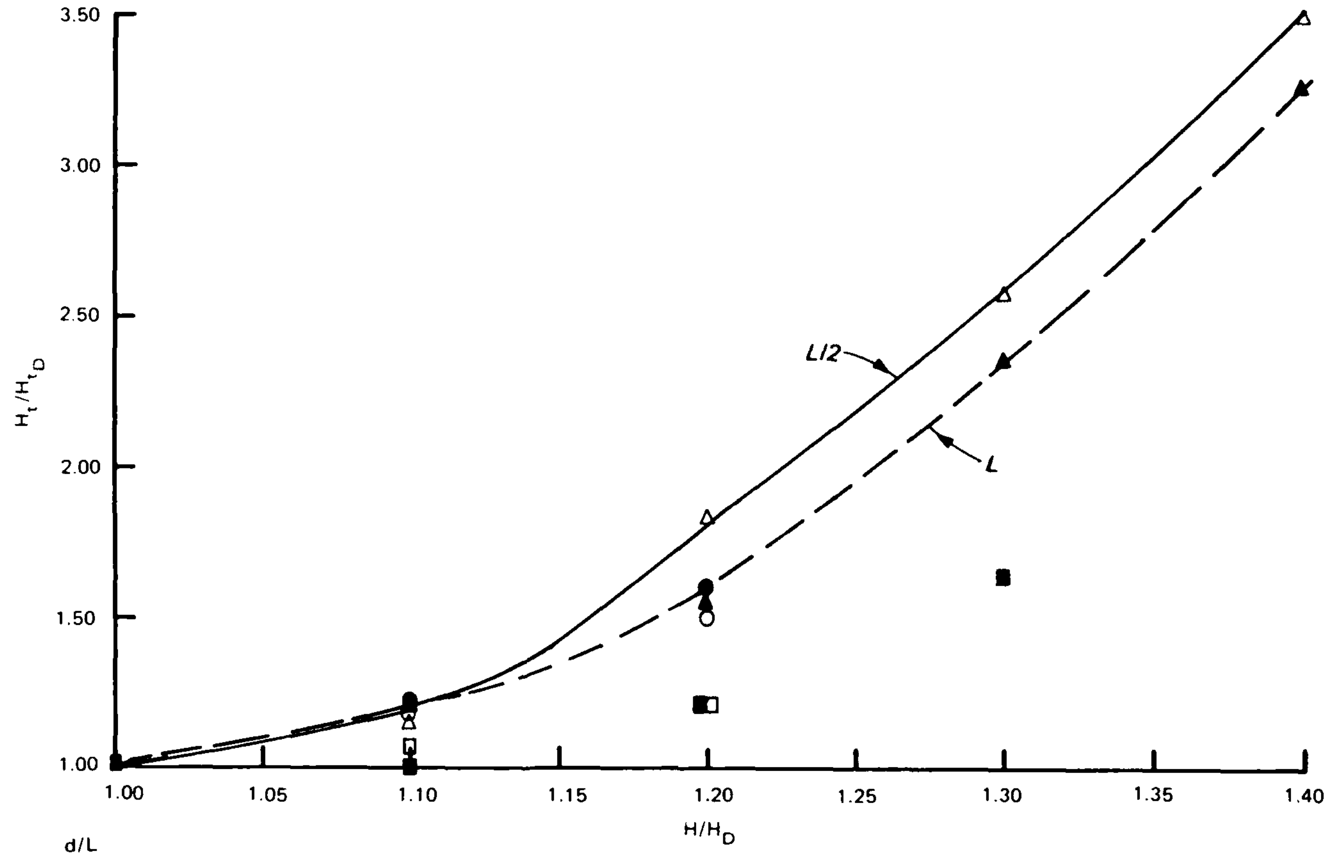


LEGEND

SYMBOLS L/2	SYMBOLS L	T, (SEC)	d/L
○	●	1.31	0.25
△	▲	1.89	0.15
□	■	2.65	0.10

NOTE: L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 1.5
DOLOS; NONBREAKING WAVES

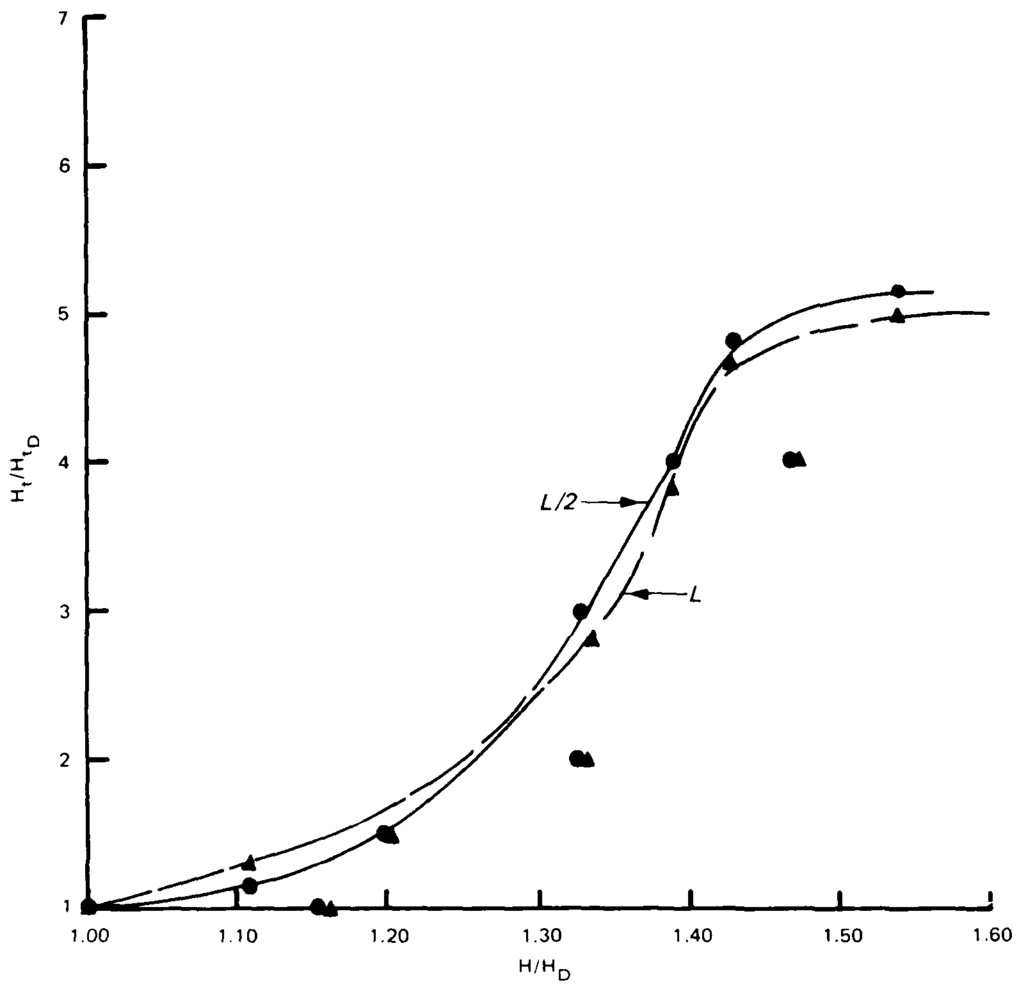


LEGEND

SYMBOLS L/2	SYMBOLS L	T, (SEC)	d/L
○	●	1.31	0.25
△	▲	1.89	0.15
□	■	2.65	0.10

NOTE L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

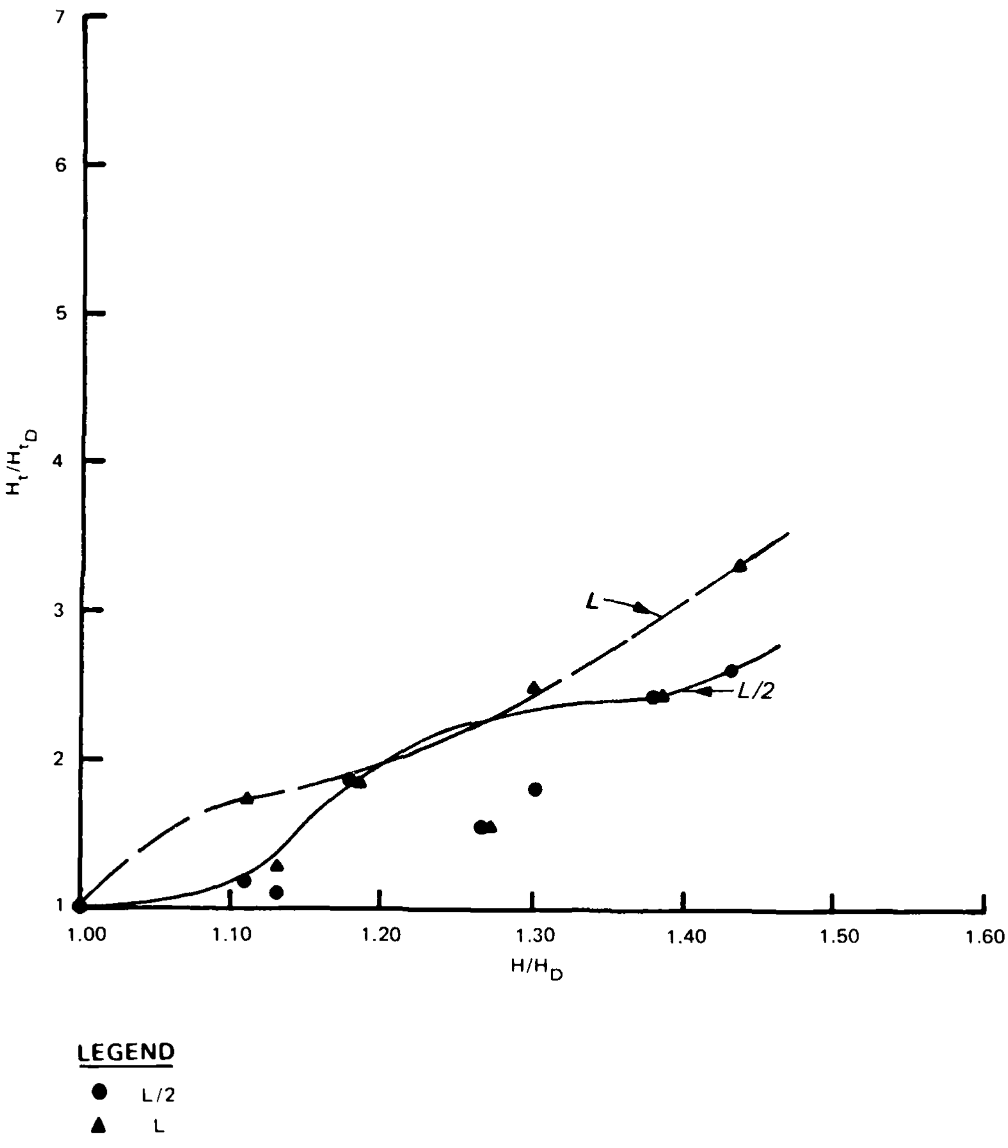
RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 2.0
DOLOS; NONBREAKING WAVES



LEGEND
● L/2
▲ L

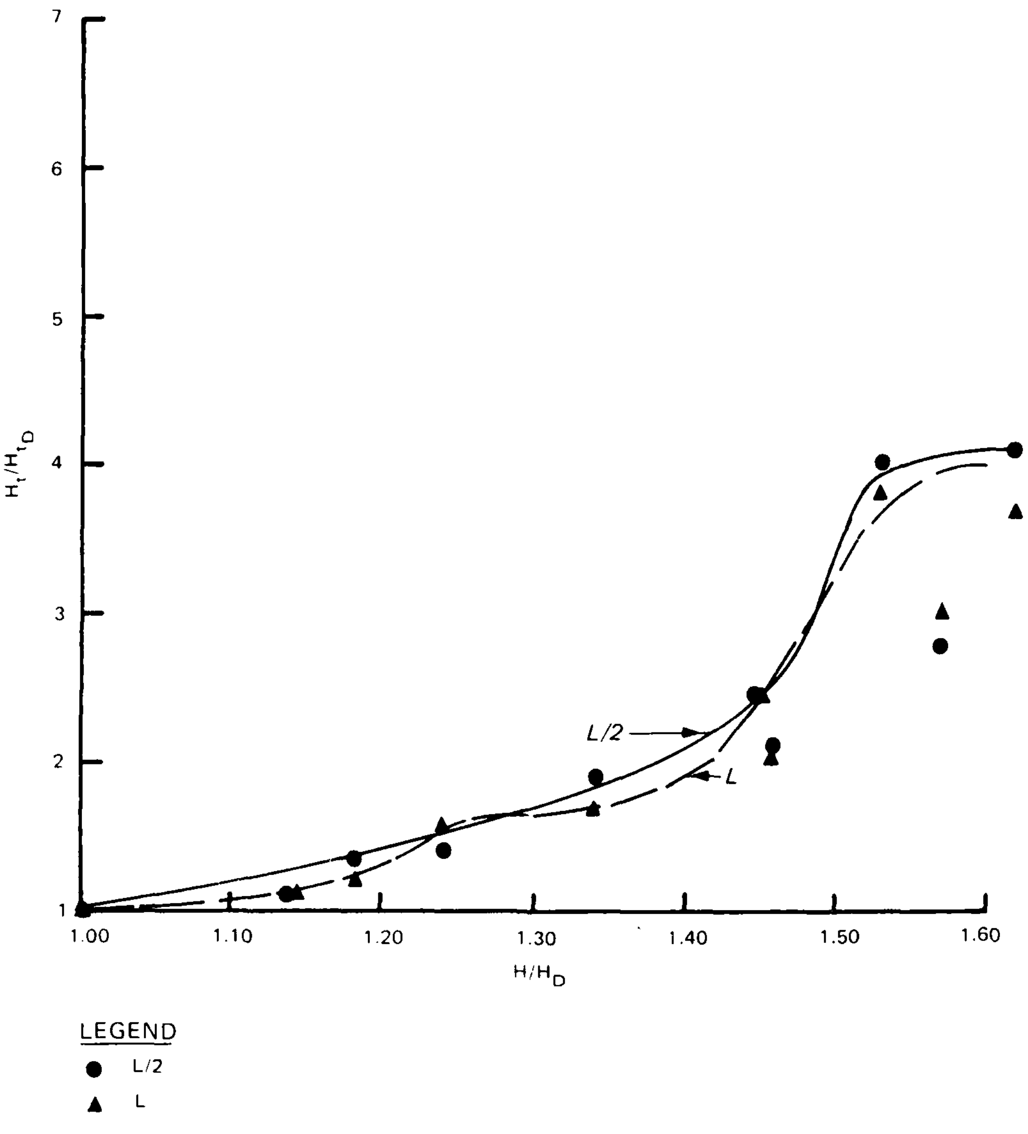
NOTE: L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 1.5
DOLOS; BREAKING WAVES



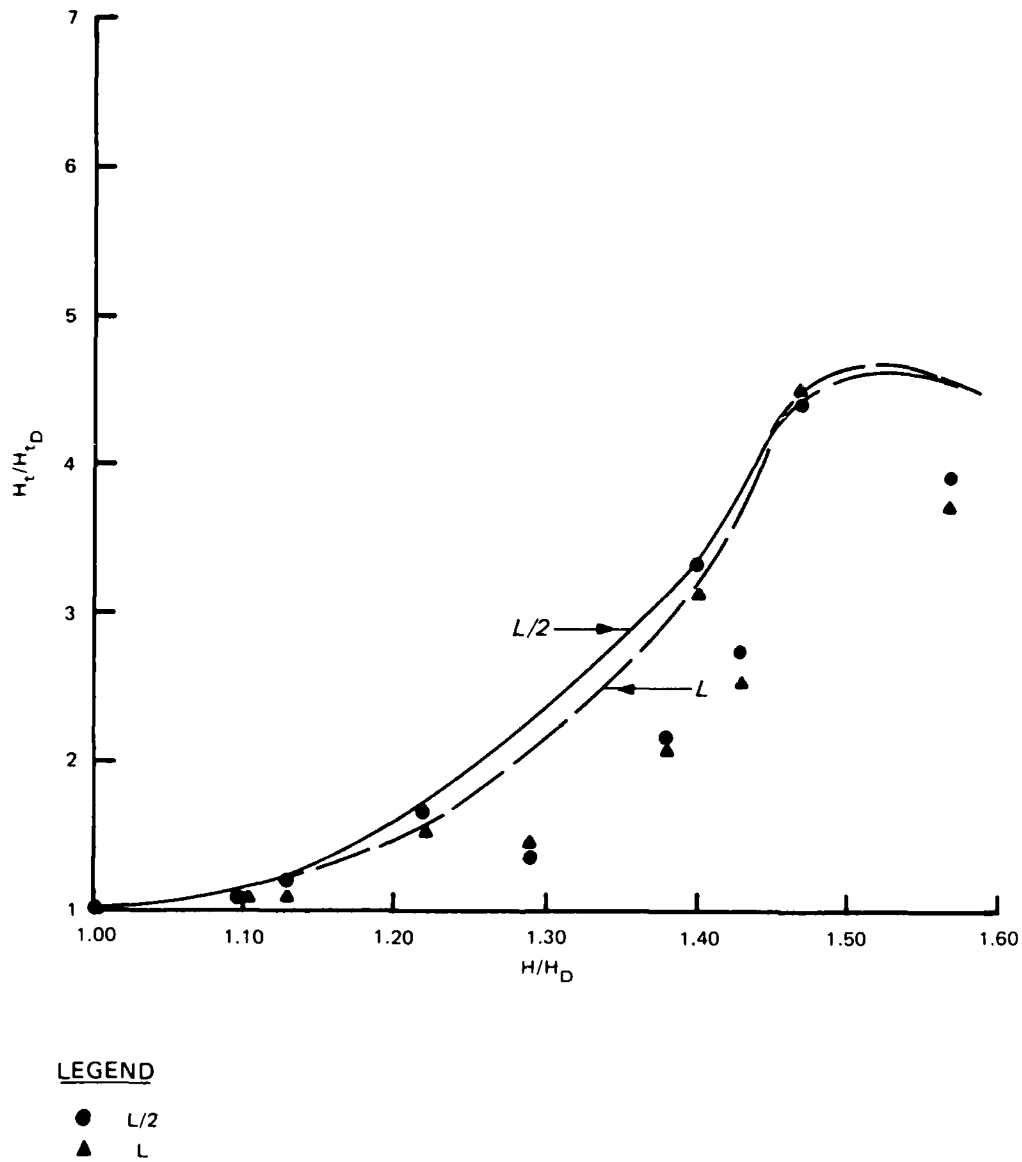
NOTE: L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 2.0
DOLOS; BREAKING WAVES



NOTE: L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 1.5
STONE; BREAKING WAVES



NOTE: L/2 AND L ARE DISTANCES IN WAVELENGTHS BEHIND CENTER LINE OF BREAKWATER AT WHICH TRANSMITTED WAVE HEIGHTS ARE MEASURED.

RELATIVE TRANSMITTED WAVE HEIGHT (H_t/H_{t_D})
VERSUS RELATIVE WAVE HEIGHT (H/H_D)
COT α = 2.0
STONE; BREAKING WAVES

APPENDIX A: NOTATION

A	Surface area, ft^2
c	Coefficient
d/L	Relative depth
g	Acceleration due to gravity, ft/sec^2
H	Wave height, ft
H/d	Relative wave height
H/L	Wave steepness
k_Δ	Shape coefficient
K_D	Stability coefficient
ℓ_a	Characteristic length of armor unit, ft
L	Length, wavelength, ft
n	Number of layers of armor units
N	Number of armor units
P	Porosity of breakwater material, percent
R_N	Reynolds stability number $= \left(g^{1/2} H^{1/2} \ell_a / \nu\right)$
T	Wave period, sec; time
W	Weight, lb
α	Angle of breakwater slope, measured from horizontal, deg
$\cot \alpha$	Reciprocal of breakwater slope
γ	Specific weight, pcf
γ_a	Specific weight of an armor unit, pcf
Δ	Shape of armor unit or underlayer material
Θ	Angle between the horizontal and the sea bottom on which the breakwater is constructed
ν	Kinematic viscosity

Subscripts

a	Refers to armor unit
D	Refers to design condition
s	Refers to stability
t	Refers to transmitted wave height
w	Refers to water in which the structure is located

END

12-86

DTIC